PNE-1400

THE BRONCO OIL SHALE STUDY

A study of the feasibility of fracturing oil shale with nuclear explosions, the extraction of oil by in situ retorting, and the design of an experiment to test this concept. Prepared by the United States Atomic Energy Commission, the United States Department of the Interior, CER Geonuclear Corporation, and the Lawrence Radiation Laboratory.

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ABSTRACT

The study was prepared cooperatively as part of the AEC's Plowshare Program by the San Francisco Operations Office of the U.S. Atomic Energy Commission, the U.S. Bureau of Mines, the University of California's Lawrence Radiation Laboratory and the CER Geonuclear Corporation, the latter acting for approximately a score of oil companies.

Part I of the study examines the feasibility of using deeply buried underground nuclear explosions to break oil shale deposits for in situ retorting, and recommends that a nuclear explosion experiment be designed to test the concept.

Oil shale is a fine grained, calcareous rock containing kerogen, a solid hydrocarbon. When kerogen is heated to temperatures over 700°F, it rapidly decomposes to produce a liquid oil similar to petroleum. Oil shale is widely distributed throughout the world, and constitutes a major hydrocarbon resource. However, most of the world's known resources, over two trillion bbls, are located in Colorado, Utah, and Wyoming. In some places the thickness of oil shale yielding 25 gal/ton reaches 2,000 feet. It is this higher grade shale that is being considered for utilization. Associated with the oil shale in these deposits are the minerals nahcolite and dawsonite, which are potential sources of soda ash and aluminum.

Efforts to develop a commercial oil shale industry date back to the mid-1800's. Conventional methods involved mining the oil shale and heating it in a retort to extract the oil. Recently interest has developed in methods to retort the oil shale underground. The nuclear concept involves firing a deeply buried, totally contained nuclear explosive to fracture the shale, which would then be retorted in place. A number of methods of retorting the broken oil shale, and associated fracture zones are described.

If successful, the utilization of nuclear explosives for this application would eliminate the necessity of mining and bringing to the surface huge quantities of shale for surface treatment and subsequent disposal of the retorted rock, increase the nation's available oil supply by allowing the economic development of vast resources of oil shale that are currently beyond the scope of any recovery technique, and permit large-scale operations with a minimum disturbance of the natural landscape.

A location in the Piceance Creek Basin in western Colorado has been investigated as a site for further studies and field investigation. The report recommends that safety and engineering field work to determine whether the location is suitable for a field test proceed simultaneously with design of a field experiment.

Part II of the study describes Project Bronco, a proposed 50-kiloton nuclear explosion experiment. The detonation will fragment and fracture a deep, thick oil shale deposit which will subsequently be retorted in place. Bronco will provide information related to: the technical and economic feasibility of the basic concept, a predictive capability for the physical effects of nuclear explosions, and the distribution of radioactivity and its behavior during retorting.

Although the Bronco experimental design is based on a potential site in the Piceance Creek Basin, a pre-shot investigation will determine whether the nominated site will meet the technical and safety criteria for a first nuclear explosion in oil shale.

Following site confirmation, holes will be drilled for fracture studies, emplacing the explosive, and for shock wave measurements. The explosion is expected to produce a chimney 230 feet across and 520 feet high (measured up from the shot point), containing over one million tons of fragmented oil shale. Fractures may extend as far as 460 feet laterally beyond the chimney edge. Post-shot drilling will reveal the size and shape of the chimney, the extent of fracturing, and the distribution of heat and radioactivity.

The final design of the in situ retorting experiment will depend on results of the post-shot exploration and on laboratory research currently under way. Due to this uncertainty of retorting design, no cost estimate is included in this report. Tentatively, mixtures of air and recycle gas will be injected via drill holes to the chimney top. Drill holes to the chimney bottom will remove off-gas, oil mist, and liquid oil. During retorting, measurements will be made of temperatures in the chimney. Samples of gas and oil will be analyzed for physical characteristics, chemical composition, and radioactive content, if any. Additional data on retorting efficiency will be obtained in post-retorting drill holes.

It is tentatively planned to follow the chimney retorting with an experimental outward moving treatment in a 45° sector of the fractured region outside the nuclear chimney.

ACKNOWLEDGMENT

The preparation of this report was a joint effort of the San Francisco Operations Office of the U.S. Atomic Energy Commission, the U.S. Bureau of Mines, the CER Geonuclear Corporation, and the Lawrence Radiation Laboratory, with technical contributions from the U.S. Geological Survey, the Oak Ridge National Laboratory, and the Nevada Operations Office of the Atomic Energy Commission.

The principal authors of Part I of the report, which deals with the overall feasibility of using nuclear explosions in the recovery of oil from oil shale, were M. A. Lekas of the Atomic Energy Commission, Bruce G. Bray of the CER Geonuclear Corporation, and Harry C. Carpenter of the U.S. Bureau of Mines. Valuable assistance in preparing this section was made by Gerald U. Dinneen, BuMines; H. H. Aronson, CER; and J. D. Downen, AEC.

The principal authors of Part II, describing the design of a nuclear explosion experiment for fracturing oil shale and for retorting it, were David B. Lombard, Lawrence Radiation Laboratory; Bruce G. Bray, CER; and Harold W. Sohns, BuMines. Contributions to this section were made by Thomas S. Sterrett, LRL; Robert S. Brundage, CER, and Harry C. Carpenter, BuMines.

Frank Stead, U.S. Geological Survey, prepared the appendix dealing with the distribution of radionuclides in ground water. C. A. Blake and D. J. Crouse, Oak Ridge National Laboratory, prepared the appendix on radioactive contaminants of shale oil. Frank Stead, John Ege, and Frank Welder, U.S. Geological Survey, prepared the appendix on the Geology and Hydrology of the Piceance Creek Basin, and R. L. Kinnaman, D. W. Hendricks, and R. A. Johnson, of the AEC's Nevada Operations Office, prepared the appendix on the safety evaluation for Bronco.

A study for a proposed project of this scope, magnitude, and advanced technology has required the efforts of many in the participating organizations, and it is not practical to name all these individuals, even though their contributions are included in the study.

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THE FEASIBILITY OF USING NUCLEAR EXPLOSIVES IN THE PRODUCTION OF SHALE OIL

by

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INTRODUCTION

Oil shale is the second most abundant fossil fuel resource in the U.S. It is exceeded only by coal, and is more plentiful than petroleum and natural gas, which together furnish over 70% of the energy consumed domestically. Oil shale is found in at least 29 states, but data on all except the Green River Formation in Colorado, Utah and Wyoming are sparse. The Green River shales represent the equivalent of about two trillion barrels of oil in place, a quantity greater than that of the world's entire petroleum reserve combined with total petroleum production to date.[1]

Oil shales do not contain liquid oil, but rather a solid organic material, kerogen, intimately associated with a mixture of minerals that make up most of the rock. Heat converts the kerogen to liquid oil, similar to crude petroleum, gas, and carbonaceous residue.

Production of oil from oil shale on a commercial scale dates back to the mid-1800's when operations were begun in Europe and Australia. In the early 1900's, industries were established in South Africa and Manchuria. A small oil shale industry was operating in the eastern U.S. in 1860, but passed out of existence when petroleum became plentiful.[1] During World War II, concern over U.S. reserves of petroleum led to renewed interest in the U.S. oil shale resources. The Bureau of Mines constructed experimental facilities near Rifle, Colorado, for process development, and a research center at Laramie, Wyoming, for basic studies. Many industrial organizations cooperated in the Bureau's research and others conducted independent research programs.[1]

Recently, interest has developed in various methods for retorting the shale in place underground. Basically these consist of injecting heat into the rock and extracting the liquefied oil through wells. This interest has developed because the costs of in situ processing might be less than those involved in mining, hauling, crushing, retorting, and disposing of tens of thousands of tons of rock daily in an aboveground operation.

Research to date indicates that a primary difficulty with in situ schemes is the lack of natural permeability of the shales, which makes it impractical to inject heat and extract the oil. If a method could be developed to provide adequate permeability in the shale, an effective in situ method might be developed. It has been demonstrated that nuclear fracturing is an effective means of increasing the permeability of large masses of rock. As demonstrated in a number of actual nuclear tests, essentially open flow permeability is produced in a central chimney zone of broken rock, and fracture permeability in the order of hundreds of millidarcys is created in an envelope surrounding the central zone. The nuclear concept involves producing a deep, totally contained, nuclear explosion to create a cylindrical chimney zone of fragmented shale, surrounded by a zone of fractured shale, which would then be retorted in place.

The Plowshare Program

The Bronco study was carried out as part of the AEC's Plowshare Program, which has the task of investigating and developing safe peaceful uses for nuclear explosives. Primary research and development is carried out for the Atomic Energy Commission by the Lawrence Radiation Laboratory. Other research work is under way by the Sandia Corporation, Oak Ridge National Laboratory, U. S. Bureau of Mines, and the U. S. Geological Survey. In addition to these organizations, a number of private companies have cooperated with the AEC in carrying out Plowshare research work.

As a result of over 200 underground nuclear experiments by the AEC, a significant body of data related to the physical effects produced by nuclear explosions in various rock types has been accumulated. The data obtained from these experiments coupled with laboratory experiments and theoretical investigations make it possible to predict certain physical effects with fair accuracy. While such data provide a base for evaluating possible oil shale applications, only an actual nuclear explosion experiment in that medium can truly evaluate the method.

At the present time, the AEC is not authorized to supply nuclear explosives and related services on a commercial basis. The AEC can, however, under the Atomic Energy Act of 1954, utilize nuclear explosives in cooperative research and development arrangements with industry, and other organizations, including demonstrations of particular applications.

The Need For Oil

Petroleum and natural gas presently supply about 73 percent of the nation's total energy requirements. These materials also are an important source of many commodities such as lubricants, building materials, fertilizers, fibers, plastics, and other petrochemicals. It is extremely important for the nation to have a continuing adequate supply of liquid and gaseous hydrocarbons.

Present forecasts are in general agreement that the domestic demand for petroleum in 1980 will be about 17 million barrels per day, which is more than 50 percent above present demand. If recent trends in the rate of discovery of petroleum continue, this substantial increase in demand will result in the use of more petroleum in the next fifteen years than will be discovered. Hence, the reserve-to-production ratio for petroleum will be substantially less in the future than it is now, probably at an undesirably low level.

There are four principal alternatives available for supplying this increase in demand for petroleum in the U. S. and thus preventing an undue reduction in petroleum reserves. Three of these alternatives are technological and one is a question of national policy beyond the scope of this study. These alternatives are:

1. Increase the rate of discovery of petroleum.
2. Obtain a greater proportion of the oil from known reservoirs by new or improved recovery methods.
3. Develop economical processes for producing liquid and gaseous fuel from alternate sources such as oil shale, coal, and tar sands.
4. Increase the proportion of demand supplied by imported oil.

Many studies and forecasts have been made concerning the potential of the three technical alternatives for meeting the greatly increased future demand for liquid fuels. A majority of these have reached the conclusion that an increased rate of discovery and greater recovery from known fields probably will not yield enough oil to meet the entire increase. As a result, production from alternate sources will be required to augment petroleum supplies.

Oil shales of the Green River Formation in Colorado, Utah, and Wyoming represent a huge potential source of liquid fuels, and efforts should be made to develop techniques that will permit the use of this resource for meeting the increased demands for liquid fuels anticipated during coming years. Many techniques are being investigated, but the one of concern to this report is the recovery of oil by the in situ retorting of shale fractured by a nuclear explosive. Although the concept is simple, its application poses many technological problems whose solution will require time and effort. Therefore, work should be started now so results will be available by the time they are needed. An experiment such as proposed in Project Bronco will solve some of these problems and delineate the magnitude of others. Hence, after completion of the experiment it should be possible to estimate the potential of this approach for supplying shale oil as a supplement to petroleum.

OIL SHALE

Nature and Occurrence

The bulk of the world's known oil shale reserves are located in the U. S. Oil shales of the Green River Formation, which are of primary interest in this study, were formed from sediments deposited in two ancient lakes in Colorado, Utah, and Wyoming. During most of their six-million-year life span, these lakes were chemically stratified into two stable zones, one atop the other. The upper layer was relatively fresh, supporting life. The lower layer, primarily a solution of sodium carbonates, was strongly basic, reducing, and virtually barren of life. Organic matter falling into this brine was digested and homogenized, then encased in the developing sediment. Upon lithification, this sediment became Green River oil shale, remarkably uniform laterally, because of its development pattern.[2]

Oil shale is a fine-grained, high density rock with essentially no permeability or porosity. It is tough, elastic, and resistant to fracture. The composition and percentage of mineral and organic matter in a rich interval of the Green River oil shale are presented in Table 1. In addition to these minerals, others, particularly nahcolite and dawsonite, were deposited toward the center of the Piceance Creek Basin.

The Green River Formation underlies approximately 16,500 square miles of the states of Colorado, Utah, and Wyoming (Table 2) (Figure 1).[3,4] Continuous oil shale sections 15 to 2,000 feet thick, which average 15 gallons of oil per ton, underlie 1,380 square miles in Colorado and represent more than one trillion barrels of oil in place.

Of this total resource, 480 billion barrels of oil are contained in shales averaging 25 gallons of oil per ton (Figure 2). Present information indicates sections averaging 25 gallons of oil per ton in Utah that are 10 or more feet thick represent 90 billion barrels of oil and those in Wyoming represent 30 billion barrels of oil.[3] It is this higher grade shale that is presently being considered for utilization.

Crude shale oil is potentially a source of fuels and chemicals similar to those presently produced from petroleum. However, shale oils contain large quantities of olefinic

TABLE 1—COMPOSITION OF OIL SHALE SECTIONS AVERAGING 25 GALLONS OF OIL PER TON IN THE MAHOGANY ZONE OF COLORADO AND UTAH[5]

		Weight Percent
Organic matter: Content of raw shale		13.8
Ultimate composition of organic fraction:		
Carbon	80.5	
Hydrogen	10.3	
Nitrogen	2.4	
Sulfur	1.0	
Oxygen	5.8	
	100.0	
Mineral matter: Content of raw shale		86.2
Estimated mineral constituents:		
Carbonates, principally dolomite	48.0	
Feldspars	21.0	
Illite	13.0	
Quartz	13.0	
Analcite and others	4.0	
Pyrite	1.0	
Total	100.0	

hydrocarbons and more oxygen, nitrogen, and sulfur derivatives of hydrocarbons than many petroleums. Consequently, petroleum refining methods, particularly catalytic processing, probably would have to be modified for the successful treatment of shale oil.

Mining and Aboveground Retorting

Since the first oil shale plants were constructed in Scotland and France over one hundred years ago, shale oil has been produced commercially at one time or another in a number of countries. However, at the present time there is significant industry only in Estonia and Manchuria while Brazil is attempting to establish one.

In the United States over the past 60 years or so, many attempts have been made to mine and retort oil shale from deposits of the Piceance Creek Basin. Since World War II, major efforts have been devoted to one mining system — the room and pillar — and to three retorting systems—those proposed by the Bureau of Mines, Union Oil Company of California, and The Oil Shale Corporation (TOSCO).

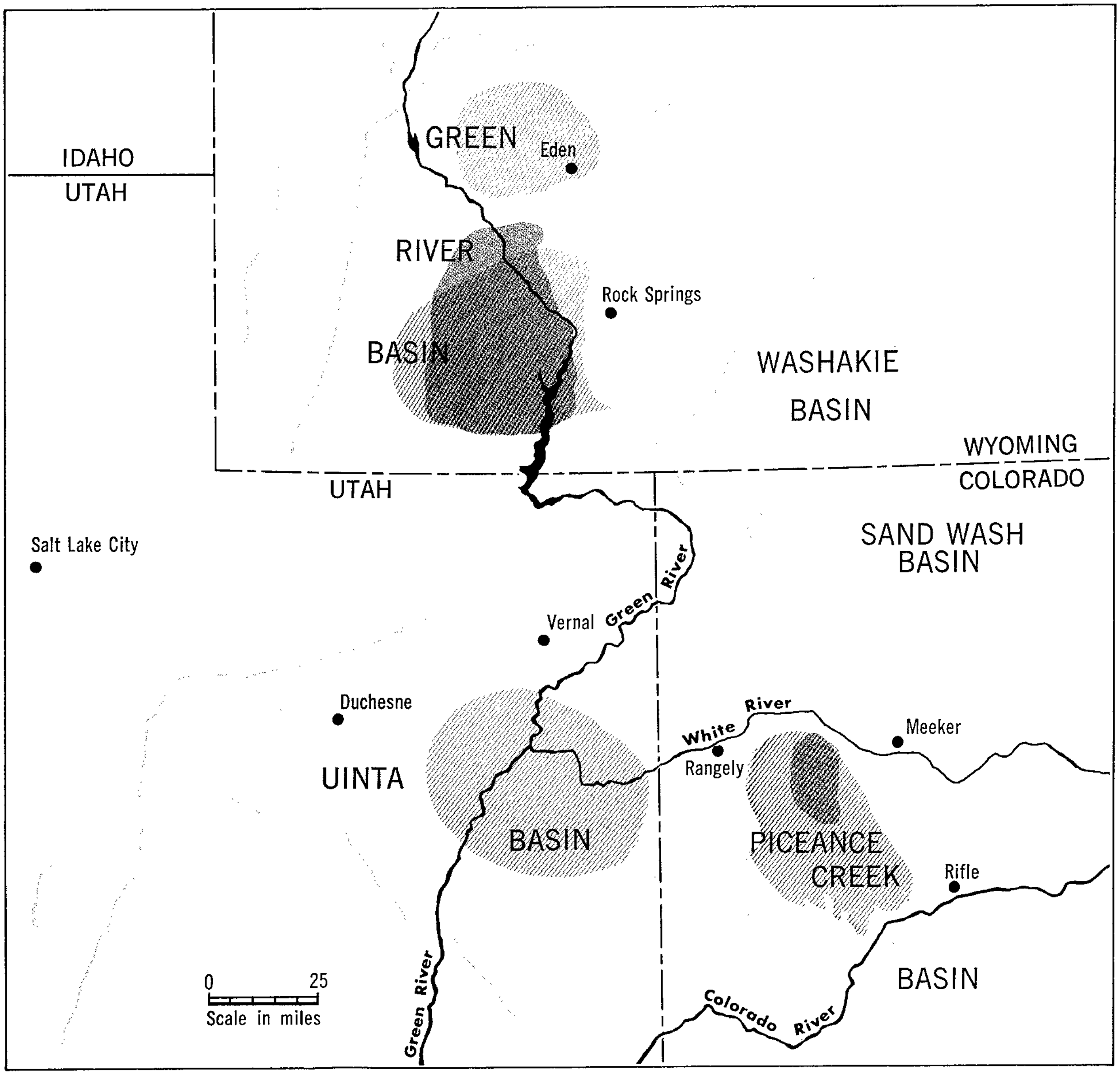
During 1944-56, pilot plant investigations of mining and retorting oil shale were conducted at Rifle, Colorado, by the Bureau of Mines.[6,7] A mine was opened to demonstrate the potentialities of a room-and-pillar operation. Of the numerous retorts studied in the Bureau of Mines program, the gas combustion retort gave the most promising results. This retort is a vertical, refractory lined vessel through which crushed shale moves downward by gravity. Recycled exhaust gases enter the bottom of the retort and are heated by the hot retorted shale as they pass upward through the vessel. Air is injected into the retort at a point approximately one-third of the way up from the bottom, and is mixed with the rising, hot recycled gases. Combustion of the gases and of some residual carbon heats the shale immediately above the combustion zone to retorting temperature. Oil vapors and gases are cooled by the incoming shale and leave the top of the retort as a mist.

In May of 1964 the pilot facilities at Rifle, which had been maintained in a standby condition since 1956, were leased by the Colorado School of Mines Research

TABLE 2 — MAJOR SHALE OIL RESERVES[5]

	Oil in place, million bbl
Australia	200
Brazil	342,000
Bulgaria	200
Burma and Thailand	17,100
Canada	34,200
China:	
Fushun, Manchuria	2,000
Other deposits	2,700
England	1,400
Estonia	17,300
France	1,400
Germany (West)	2,000
Israel	20
Italy	34,300
Malagasy Republic	200
New Zealand	200
Republic of the Congo (former Belgian Congo)	103,000
Republic of South Africa	30
Scotland	600
Spain	300
Sweden	2,800
United States[a]	2,000,000
U.S.S.R.	6,800
Yugoslavia	1,400
Total	2,570,050

[a]Value in reference (5) updated on basis of reference (3).



Adapted partly from Duncan & Swanson, 1965, fig. 3, and Culbertson, 1966, fig. 1.

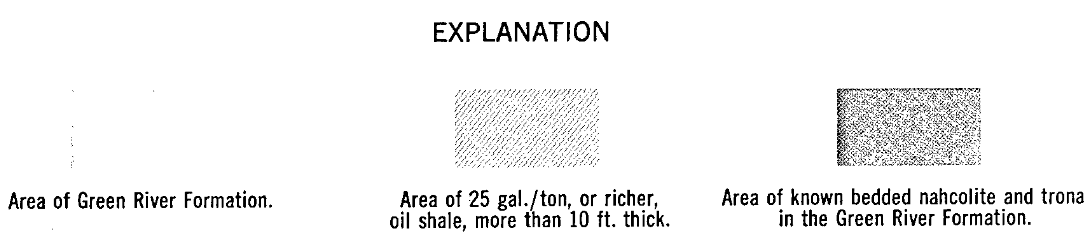


Figure 1. Distribution of the Green River Formation of Colorado, Utah and Wyoming.

Foundation and are being operated under a research contract with six oil companies: Mobil Oil Corporation, which acts as project manager, Humble Oil and Refining Company, Phillips Petroleum Company, Sinclair Oil and Gas Company, Pan American Petroleum Corporation, and Continental Oil Company. The research program, to cost about seven million dollars, is investigating the gas combustion retorting method, and improved mining techniques.

Union Oil Company of California has developed a retorting system[8] utilizing a vertical refractory lined vessel through which the shale is moved upward by an unusual charging mechanism referred to as a "rock pump." The retort is heated by passing air downward to burn the organic matter remaining on the retorted shale. The oil produced in the retorting zone is condensed on the cool, incoming shale, and flows over it to an outlet at the bottom of the retort. During the period 1955-1958, a room-and-pillar mine and a retort processing about 1,200 tons of shale per day were operated at a site on Parachute Creek north of Grand Valley, Colorado.[9]

Colony Development Company has conducted operations, also on Parachute Creek, since 1964 in an effort to develop the TOSCO retorting process.[10] The retort used in this process is a rotary-type kiln utilizing contact with ceramic balls, heated in a separate vessel, to accomplish retorting. The Colony operations included construction of a "semi-works" TOSCO retort, and the attendant opening of a room-and-pillar mine.

In addition to the preceding approaches, a number of other methods of mining and surface retorting have been discussed in the literature.

In Situ Treating

Because mining, transporting, crushing, and disposal of spent shale make up most of the present cost of producing shale oil, treating shale in place to produce oil is being investigated as a means of reducing the cost of shale oil recovery. This approach has other attractive features. It may be applicable to deposits of various thicknesses, grades, and amounts of overburden, does not disfigure the surface, and eliminates the necessity of disposing of large quantities of spent shale. A prerequisite to in place treatment is creation of adequate permeability in the shale bed. A number of techniques, including fracturing with nuclear explosions, have been suggested to accomplish this.

Sinclair Oil and Gas Company began studying the feasibility of in situ retorting of oil shale in 1953.[11] From these tests and subsequent ones made during the following year, it was concluded that communication between wells could be established through induced and natural fracture systems, that wells could be ignited successfully although high pressures were required to maintain injected rates during the heating period, and that combustion could be established and maintained in the shale bed. More recently Sinclair has been conducting extensive field research at a site on Yellow Creek in Rio Blanco County, Colorado.

One of the newer in situ shale oil recovery processes has been patented by Equity Oil Company of Salt Lake City.[12,13] This process employs injection of hot natural gas to retort the shale and it has been successfully field tested in the Piceance Creek Basin. One injection well and four producing wells were drilled into the shale formation. Gas was compressed to about 500 psi, heated to the desired temperature level, and delivered through insulated tubing to the retorting zone.

In situ field tests have also been conducted by Mobil Oil Corporation, but little information on their operation has been released.

The Bureau of Mines is presently studying two methods for creating permeability. The first uses high-voltage electricity to fracture the shale at predetermined locations approximately parallel to the shale bedding planes. Field tests are being conducted in shale beds near Rock Springs, Wyoming, to determine whether oil shale under pressure of overburden responds the same to the passage of high-voltage electricity as do unrestrained blocks in the laboratory.[14] The second approach, under way at the same field location, is a study of the detonation of liquid nitroglycerine, injected into the natural or induced permeable zones, to create additional fracturing in oil shale beds.[15]

The use of a nuclear explosion to fracture very large quantities of shale, several million tons at one time, is another approach and is the one of principal interest in this report. This technique is primarily applicable to relatively thick shale intervals under substantial overburden. Although minimum specifications for the amounts of shale and overburden required cannot be established definitely until after data are available from one or more experimental nuclear tests in oil shale, the technique should be applicable to a large area of the Piceance Creek Basin.

For example, if a 200-foot interval of oil shale averaging 25 gallons of oil per ton under an overburden of 1,000 feet is assumed adequate, an area of about 360 square miles in Colorado alone would be amenable to the technique. This area, which contains intervals of shale from 200 to 2,000 feet thick averaging 25 gallons of oil per ton, would represent on the order of 400 billion barrels

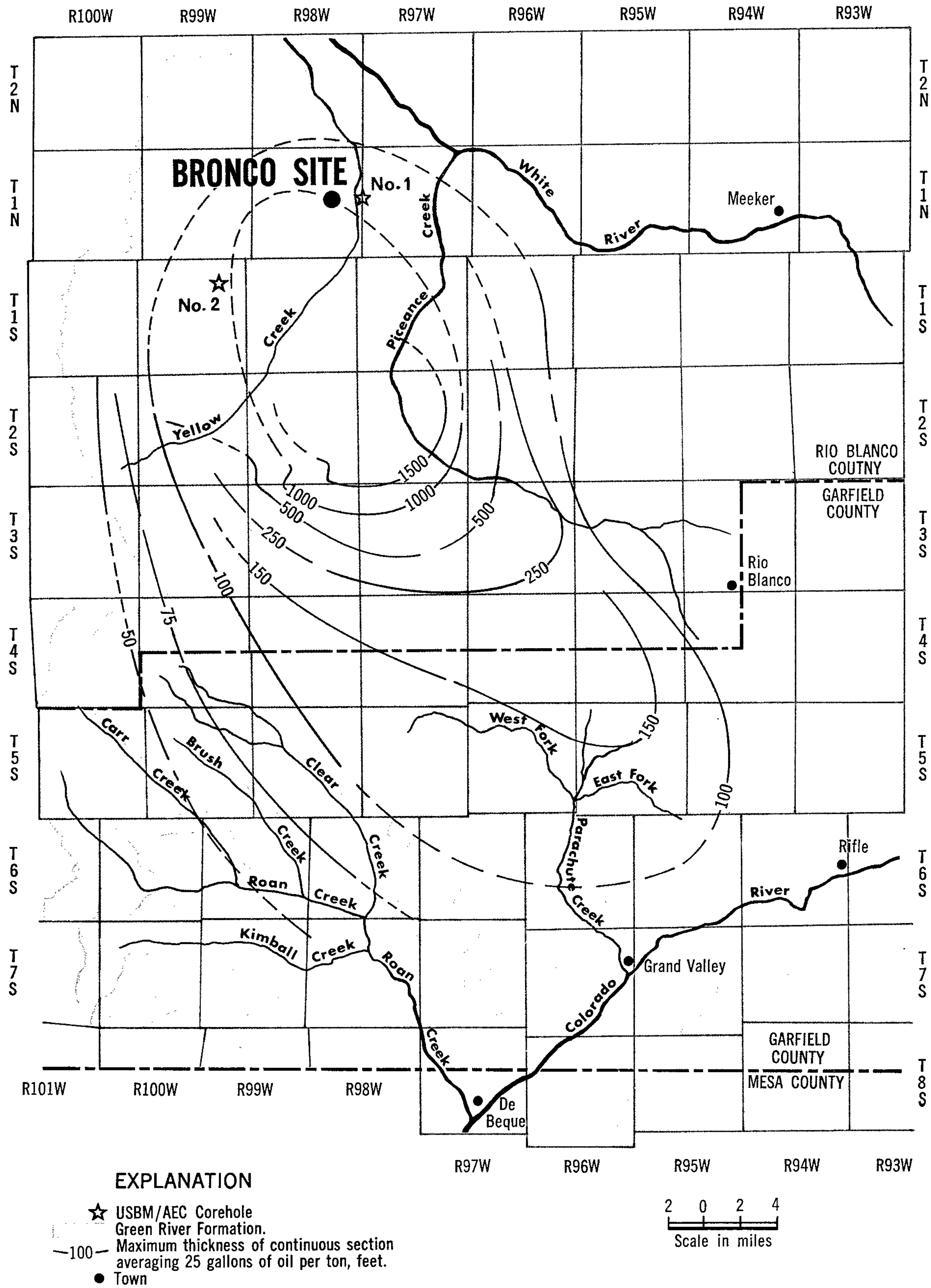


Figure 2. Isopachous map of 25-gallon-per-ton oil shale, Piceance Creek Basin, Colorado.

of oil in place. (The recovery technique may not be applicable at some locations in the area due to extensive concentrations of saline minerals, excessive quantities of water, land status problems, or other factors.)

At present there are insufficient data on the oil shales in Utah and Wyoming to predict the extent of applicability of the technique in these states.

Dawsonite and Nahcolite

Deposits of nahcolite (Na HCO_3) and dawsonite [NaAl (CO_3) $(OH)_2$] are distributed through a tremendous volume of oil rich shale in the central part of the Piceance Creek Basin (Figure 1). Although there is no current recovery of these minerals in the basin, interest is being expressed on their potential as raw materials for producing aluminum and soda ash. Limited research to date indicates that the minerals might be extracted from a nuclear chimney by in place aqueous leaching methods.[16]

Laboratory investigations of methods of extracting nahcolite and dawsonite from oil shale are being conducted by the Bureau of Mines.

FRACTURING OIL SHALE WITH NUCLEAR EXPLOSIVES

Cavity and Chimney Formation

Upon detonation, the energy of a nuclear explosive is developed in microseconds, vaporizing the adjacent rock, and farther out, melting and crushing the rock. The expanding gases thrust the surrounding rock radially outward, creating, in fractions of a second, a spherical cavity within the earth, filled with vaporized and melted rock (Figure 3). The radius of the cavity is a function of the energy yield of the explosive and, to a lesser extent, the rock characteristics, and the depth of burial.

The melted rock that initially lines the walls of the cavity collects in a pool at the bottom of the cavity prior to cavity collapse. Most of the solid radioactive fission products are trapped in this melt, which solidifies into a refractory slag that effectively immobilizes the entrapped radionuclides.

After a period of time ranging from seconds to hours, the roof of the cavity collapses, and a cylindrical column (chimney) of broken rock develops upward as the cavity fills with rock falling from the roof. The volume of the cavity is translated into interstitial space between the fallen rock fragments, with a void space at the top.

Temperature

In deeply buried detonations, 95% of the energy released by the explosion (10^{12} calories per kiloton) remains in the chimney area as residual thermal energy.[17] Initially the bulk of this heat is in the melt, but within a few months the heat is distributed throughout the mass of broken rock by conduction to the rock that has fallen into the melt pool and by refluxing of water and other fluids through the chimney zone. The net result is that within a few months, the high temperature of the melt zone has been dissipated and the chimney rubble and adjacent rock have been heated to temperatures of 100 to 200 degrees F.

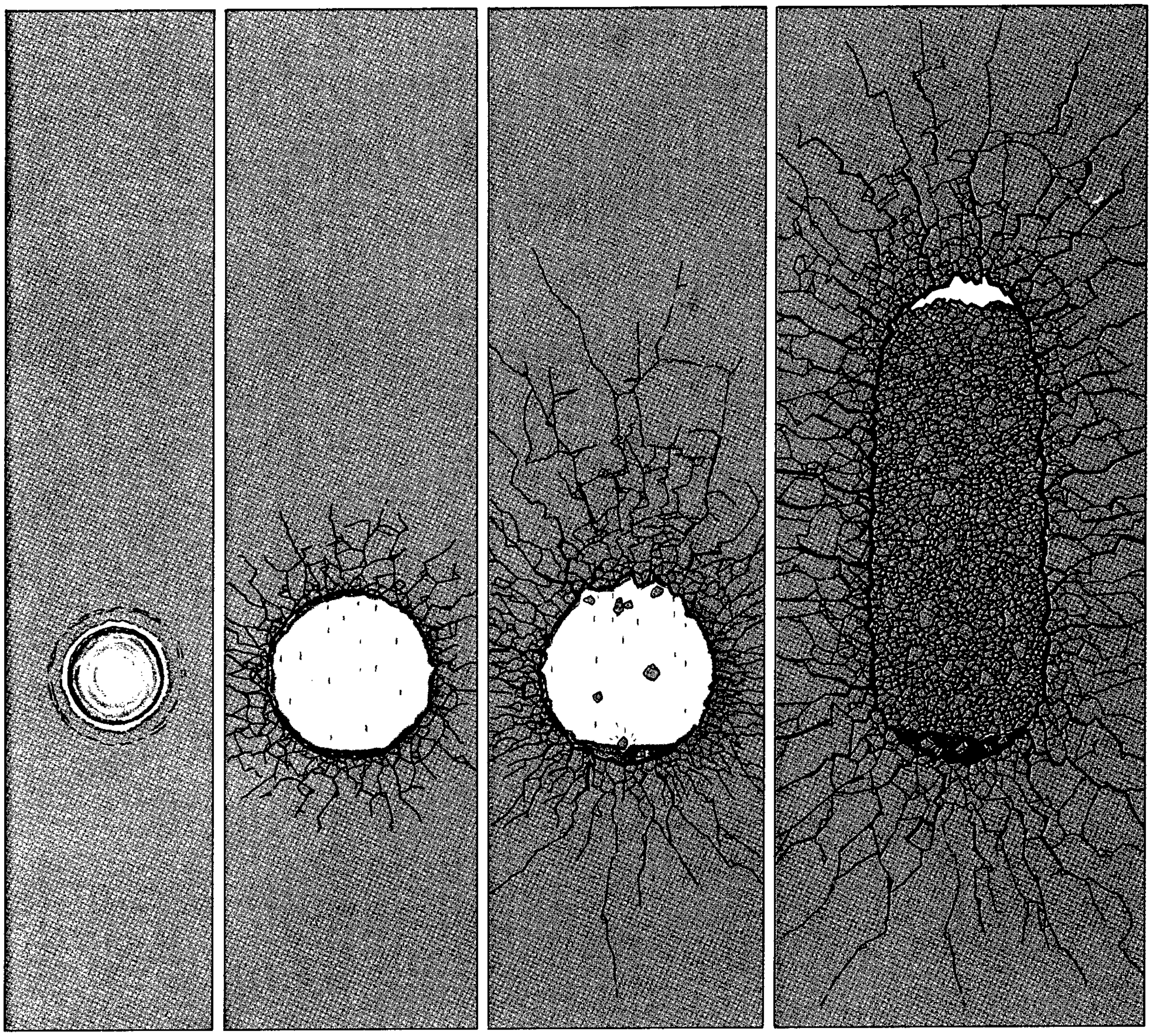
Post-shot Environment

As an example of the environment that might exist in the shale after a nuclear blast, we can consider the case of a 50 kt shot at the base of a 1,000-foot-thick oil shale section at a depth of 3,000 feet. On the basis of experiments in other types of rock, it is postulated that the effect of this shot would be to create a chimney 230 feet in diameter and 520 feet high.

Initially, the interstices of the permeable chimney would be filled with water vapor and other gases from the vaporized and melted oil shale that surrounded the explosive. The lower hemisphere of the cavity would contain most of the radioactive fission products of the explosion entrapped in the refractory slag, but any volatile species, those with volatile or gaseous precursors and any species present in organic-metallic compounds would be dispersed throughout the chimney. The hydrogen compounds: water, hydrocarbon gases, and liquid oil, would probably be somewhat radioactive due to the exchange of tritium with hydrogen in the early, high temperature environment of the cavity.

Fragmentation and Fracturing

The maximum particle size in the chimney will generally be determined by the joint spacing in the rock. It will grade downward, in a fully unsorted fashion, to sand size grains. The chimney is thus a highly permeable mass of broken and displaced rock surrounded with relatively unbroken rock on all sides as shown in Fig-



A typical sequence of events when a nuclear explosion is detonated underground. Different geological formations would cause variations in the general outcome.

1. During the first few micro-seconds the explosion creates a spherical cavity filled with hot gases at extremely high pressures.

2. The high pressure forces the cavity to expand. When the pressure inside the cavity is equal to that of the overburden, expansion ceases.

3. As the cavity cools, some of the gases liquefy and the molten rock runs to the bottom. Within a few seconds the cavity roof begins to collapse.

4. Falling rock from the roof creates the chimney of broken rock, which is typical of underground explosions. As the chimney rises to a point where the roof becomes self supporting, its growth ceases. Surrounding the chimney is a broad, high fractured area which results from the shock of the nuclear explosion.

Figure 3. Sequence of events in an underground nuclear detonation.

ure 4. The void space of the chimney will be about 20 to 30 percent, and the radius of the chimney approximately equal to the cavity radius. Generally the height of the chimney will be four to five times the cavity radius, varying with the rock type.

The bulk permeability of the rock surrounding the chimney is increased through fractures created by the shock wave, and by movement on pre-existing planes of weakness, primarily joints and bedding planes. Measurements made in granite indicate that increases in permeability of up to one darcy occur for horizontal distances of at least 3 cavity radii from the shot point.[18] Above the shot point, fractures would be expected to extend for distances of 6 to 8 cavity radii and below for about 1½ radii.[19]

Safety and Product Contamination

Safety considerations involved with effects at the time of detonation are:

1. Ground motion produced by the explosion.
2. Possibility of accidental release of the radioactive gases from the explosion to the atmosphere.
3. The possibility of radioactivity from the explosion entering the ground water system.

These "operational" safety considerations are discussed on page 18 and in Appendix D, page 58.

Of lesser concern are potential problems due to radioactivity entering the shale oil and exhaust gases. Radiation from the produced crude oil and the retort gases in the recovery plant may require precautions for worker protection. It is conceivable that exhaust gases from the retorts would contain low levels of gaseous radioactive material and some entrained solids and liquids. Release of such gases would be controlled by use of a monitoring stack comparable to systems routinely used at power reactor plants. Entrained material in the gas system would be removed by filtration.

Laboratory scale experiments are being carried out (Appendix B, page 49) to investigate the possibility of radioactive material being carried through the recovery process and appearing in the shale oil products. These studies will provide a better basis for predicting the behavior of the various radionuclides in the processing cycle. On the basis of preliminary results, it appears possible that contamination of oil could take place through the exchange of tritium (formed by a fusion explosion) with hydrocarbon vapors and water during the blast, and also during the retorting operation. This effect can be minimized by draining all liquids from the chimney, prior to retorting, and disposing of the early runs of produced oil. Any disposal of radioactive wastes would be in compliance with appropriate AEC regulations.

IN SITU RETORTING OF FRACTURED OIL SHALE

Retorting Chimney

Since 1958 many investigators [20,21,22,23] have considered the feasibility of using nuclear explosives to fracture oil shale to be followed by recovery of the oil from the fractured mass of shale by retorting it in place. Many of the proposals for in place retorting are modifications and extensions of a conventional batch retorting process.[20] In such a process, a combustion zone is initiated at the top of the retort and moved downward through the bed of shale at a predetermined rate. Control of the rate of movement of the zone is achieved by manipulation of the flow rate of recycle gas and air. As the hot gases generated by combustion of some of the organic matter in the shale move downward through the shale bed they heat the shale to retorting temperatures (about 700°F) and carry with them the liquid and gaseous products that are released from the shale. The process stream leaves the retort near the bottom and is cooled so that the liquid products may be removed from it.

Other proposals were modifications of in situ thermal techniques used in recovering petroleum.[21] One technique consists of igniting the oil around an injection well in a reservoir and driving the combustion zone through the reservoir toward producing wells with compressed air, with or without recycle gas. Combustion produces hot gases which force the oil and water to producing wells. Another technique, known as reverse combustion, consists of moving the burning zone through the formation countercurrently to air flow. This technique offers advantages when the oil in the reservoir has a relatively high pour point because the oil passes through the heated portion of the reservoir as it travels to the production well. Other concepts would inject hot gases, either inert or reactive, into the formation.

The success of the in situ retorting following nuclear fracturing will depend largely upon:

1. The degree to which mass permeability can be created by the nuclear explosion.
2. The average size of the shale pieces resulting from collapse of the chimney.
3. Ability to control the combustion front and maintain a uniform rate of advance.

The characteristics of the broken mass of shale produced by the explosion cannot be predicted in detail, but are expected to be similar to those of the rubble which has been produced by explosions in other rock types. Particle size distribution studies have been made for oil shale from mine roof falls[24] and from nuclear chimneys in other rock types.[25] It is expected that most of the pieces in a nuclear chimney in oil shale would be less than 4 feet in maximum dimension. Studies also show that the bulk permeability of the rubble would be higher and that the bulk porosity would be about 20 to 30 percent.[19]

If the average size of the shale pieces in the rubble column tends to be too large to furnish sufficient carbon as fuel for the process, recycle gas or a small part of the oil produced may be used to furnish the additional energy required.[26] An alternate method might be to use an inert gas heated in a surface installation as the heat transfer medium for the recovery operation. Details of the recovery process, will be developed after results achieved by the nuclear explosion have been thoroughly evaluated.

Retorting Fractures

The recovery of oil from the fractured zone surrounding the nuclear chimney as well as from the rubble in the chimney itself will be investigated. The substantial difference in permeability between the chimney and surrounding fractured zones, as well as variations in permeability at different locations within the fractured zone, will be a major factor in selecting conditions for a recovery method; for example, in choosing between horizontal and vertical passage of a heating gas. Hence, such choices will have to await detailed evaluation of the results of an experimental shot. It may be possible to modify techniques developed for the fractured zone around a single nuclear chimney to make them suitable for recovering the oil from the fractured zones between chimneys of a multiple-shot operation.

Experimental Investigations

In order to gather information necessary to design the nuclear retort, a series of investigations are being carried out at the Bureau of Mines Petroleum Research Center at Laramie. An experimental aboveground retort, with a capacity of about ten tons of shale, was put into operation in January of 1965 (Figure 5). The retort was designed to study some variables considered important in retorting a nuclear chimney. Results have shown that yields of oil as high as 80% of Fischer Assay can be obtained by retorting mine run oil shale containing pieces as large as 20 inches in two dimensions. Other work indicates that oil-recovery efficiency is a function not only of the operating variables such as air rate, recycle gas rate, retorting temperature, etc., but also of the maximum particle size. Particle size also determines the quantity of residual carbon that is available for fuel for the combustion phase of the process. Air can contact only the carbon at or fairly close to the surface of the shale pieces during the time they are in the combustion zone because of the low permeability of oil shale. The amount of carbon available for combustion, therefore, is determined largely by the surface area or particle size of the shale mass.

Investigations by the BuMines[27] on the strength of retorted oil shale demonstrate that there is a rapid loss of compressive strength on retorting of higher grade shale. To investigate the effect that this would have on a column of broken oil shale under retorting conditions, a dynamic retort was constructed and put in operation in June, 1967. The retort is designed to maintain a constant load in a column of broken shale during retorting, and measure changes in volume of the rock column and its permeability as retorting progresses.

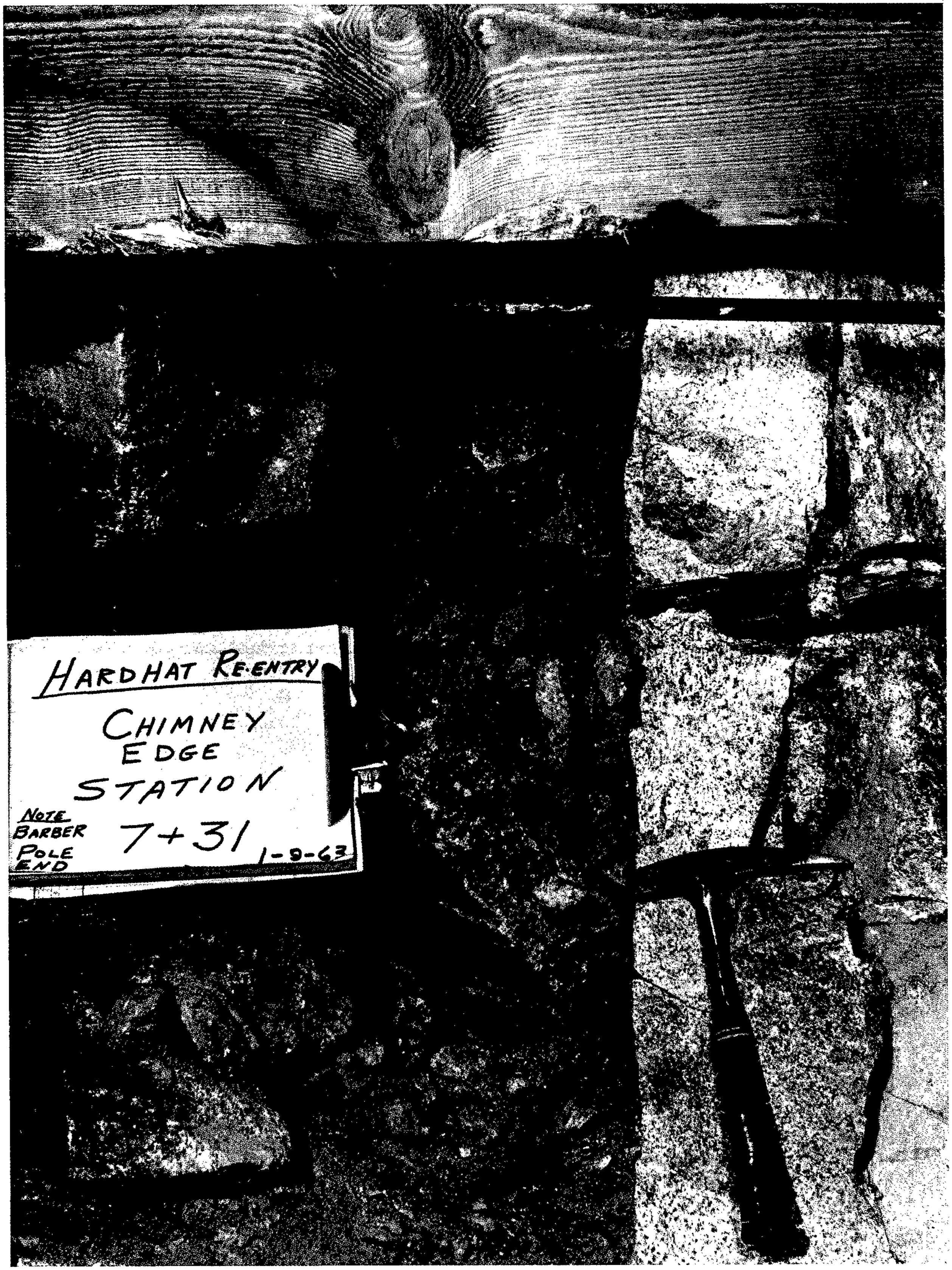


Figure 4. Hardhat Chimney (granodiorite) showing contact between fragmented rock in the chimney and the fractured rock adjacent to the chimney.

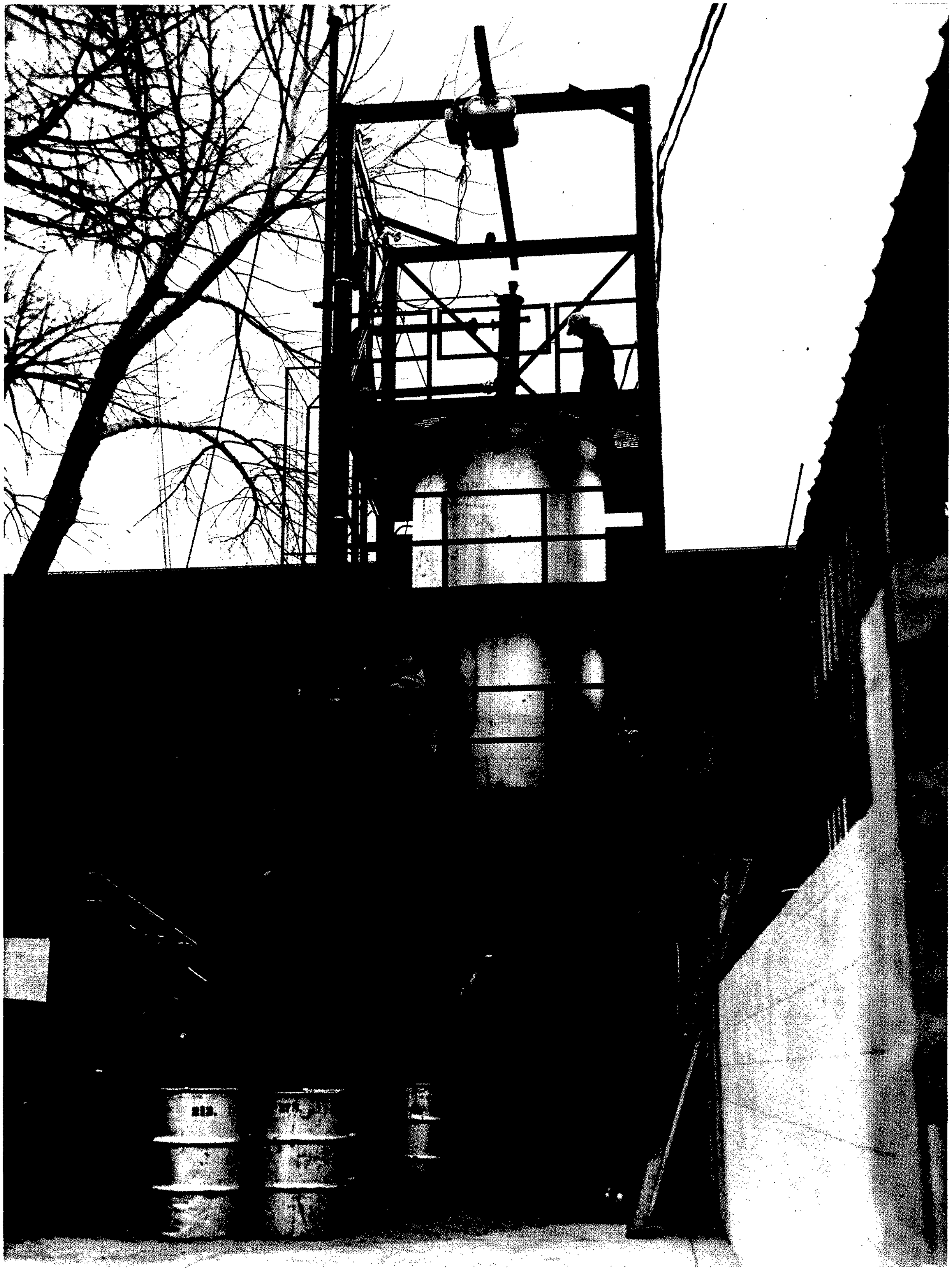


Figure 5. BuMines/AEC aboveground experimental shale oil retort, Laramie, Wyoming.

CONSIDERATIONS FOR FUTURE COMMERCIAL SCALE OPERATIONS

The future commercial development of the oil shale resources in the Piceance Basin will probably require not only recovery from isolated chimneys such as that contemplated for the Bronco experiment, but from a regular development pattern of multiple chimneys to optimize oil recovery and conserve the total resource.[22] Data are necessary from single explosion experiments to refine the technical and economic calculations for these concepts, and allow selection of the optimum process.

One proposed concept envisions the interconnection of a number of collapsed chimneys, forming one large fragmented rubble zone which could be treated as a single retort or plant. It was suggested that several such plants could be created in a consecutive manner with pillars of relatively undisturbed shale between, as shown in Figure 6. A second concept envisions overall development of the resource, such as shown in Figure 7. In this pattern, instead of interconnection of the actual chimneys, the fractured zones surrounding the chimneys would intersect providing flowpaths for fluids over the entire developed area.[22] Both concepts have advantages and disadvantages, the answers to which are largely a matter of conjecture with current technology. Answers can only come with experimental determination of a nuclear explosion environment in oil shale and solution of attendant retort operating problems.

Data to be obtained from the proposed Project Bronco experiment will help to supply answers to such current unknowns as:

1. Cavity characteristics (radius, height, bulking).
2. Fracture characteristics (density, extent, block size and orientation).
3. Chimney rubble size and bulk permeability.
4. Optimum treatment methods and shale oil recovery factors.
5. Operating pressure in both chimney and fracture zones.
6. Retorting temperatures.
7. Air injection and recycle gas requirements.
8. Effects of possible channeling of fluids.
9. Heat transfer characteristics, and methods.
10. Behavior of hot shale under pressure of the column of broken oil shale.
11. Physical characteristics of spent shale.

Appropriate economic factors applied to these data will help to determine the optimum distance between explosions for commercial basin development.

On the basis of information available today, it is not possible to accurately predict the cost of producing shale oil by the nuclear method on a commercial scale. It is possible, however, to postulate a set of reasonable assumptions and calculate profitable recovery of shale oil. It is also possible, with another set of equally logical assumptions, to calculate that shale oil recovery is uneconomic in today's market.

There are three primary technical assumptions required in calculating the recovery of shale oil from a nuclear chimney. They are:

1. The size of the chimney and, hence, the volume of oil shale available for subsequent in situ treatment. Explosions in water bearing rocks indicate that the cavity size, and therefore the amount of broken rock in the chimney is related to the water content of the rock.[19,31] It is expected that the kerogen bearing oil shale would behave similarly. On the other hand, experience with massive, relatively elastic rocks suggests that a smaller chimney would be formed.
2. The percent recovery of oil from the broken oil shale in the chimney. The uncertainty is primarily due to the wide range of rubble size contained in the chimney. It is assumed that retorting of the rubble will give an oil recovery of 50 to 70 percent of Fischer Assay.
3. The pressure and air (or gas treatment) rate at which the recovery operations will take place. Questions on the effect of the hydrology of the basin on the nuclear chimney and attendant recovery operations must be answered to define these quantities. The chimney may exist approximately as a tight closed chamber such that low pressure surface retorting conditions may be used. Alternatively, if, the hydrology is such that the chimney treatment must be operated at higher pressure, or at a hydrostatic head of 1,000 psi or above, the total investment and operating costs are substantially increased.

"The effects of these assumptions on the variation in expense of rock breakage and retort operations can result in wide variations in cost. For example, calculations based on using a 200-kiloton device to produce a cavity with a 210-foot radius and on a 70 percent recovery of the available oil at an operating pressure of 50 psig can show a favorable economic picture. With an alternate set of assumptions, the same size device might produce a cavity with a radius of 178 feet and only 50 percent recovery at a pressure of 1,000 psig. This second alternative would be uneconomic and would result in a cost per barrel of oil roughly 4 times larger than the first case.

In addition to the cost of fracturing and retorting the oil shale, the following costs must be accounted for to arrive at a total cost:

1. Lease expenses.
2. State and Federal income taxes and ad valorem taxes.
3. Interest expense on investment.
4. Gathering system and pipeline tariffs to refinery locations.
5. Royalty.
6. Hydrogenation or pretreatment.

It is obvious that the total production cost for oil from oil shale will be dependent on these items which in turn may vary considerably. They are not, however, primarily dependent on the nuclear technique. Therefore, it is important to carry out this project to define the technical parameters, so that definitive studies can be made of the economics of a large scale, commercial operation.

AN EXPERIMENT IN OIL SHALE

Location

Investigations for a location for the Bronco experiment were initiated in 1964. Interest centered on the Piceance Creek Basin, as the basin represented the major part of the nation's reserve of oil shale, and was expected to contain shales of sufficient thickness and grade to be satisfactory for the experiment. As a result of this investigation, two exploratory core holes were drilled by the BuMines/AEC in 1965 and 1966 to gather specific information on the shales in the northern part of the basin.

The USBM/AEC Colorado Core Hole No. 1 was drilled on Yellow Creek in the northern Piceance Creek Basin. In 1966, USBM/AEC Core Hole No. 2 was drilled at Duck Creek, 8 miles to the southwest. Information gathered in this program substantially increased earlier estimates of the thickness and extent of oil shale deposits in this region. Unexpected underground water was encountered in both holes. In each, however, thick sections of oil shale with limited water content were identified. The exploration also showed that the deposits of halite associated with the occurrence of oil shale in the central part of the Basin do not extend to the north.

Review of the results of the drilling indicated that the area near Core Hole No. 1 appeared to be satisfactory both from the standpoint of the nuclear detonation and the subsequent retorting. However, further drilling near this location will be necessary to confirm the suitability of the site.

The tentative location has been identified on public lands in Section 15, T1N, R98W, Rio Blanco County, Colorado, about 23 miles east of Rangely, 80 miles northeast of Grand Junction and 23 miles west of Meeker. The location is at an elevation of approximately 6,450 feet on a broad drainage divide between Yellow Creek and Barcus Creek, shown in Figure 8. It lies in the center of a broad basin-like plateau area. Annual precipitation varies from 15 to 20 inches, with the majority falling during the late fall and winter. The upland areas are covered by range grass and sagebrush, with cedar and pinon thickets on the steeper north facing slopes. The smaller streams in the area are intermittent. The area is sparsely populated, and is used as cattle range during the spring, summer and fall. The more remote areas are inhabited by deer, elk and bear, as well as a variety of smaller animals.

Geology and Hydrology

In the Piceance Creek Basin, oil shale occurs in the Parachute Creek member of the Green River Formation (Figure 9). Dawsonite, nahcolite, halite and other sodium minerals are comingled with kerogen-bearing marlstone, and form a saline rich zone in the lower half of the Member, reaching a maximum thickness of 1,200 feet. The top of the saline rich zone is a dissolution surface overlain by a zone of leached oil shale several hundred feet thick from which the water soluble minerals have been removed by ground water. The zone is water bearing and active removal of water soluble minerals may still be taking place (Appendix C, page 50).

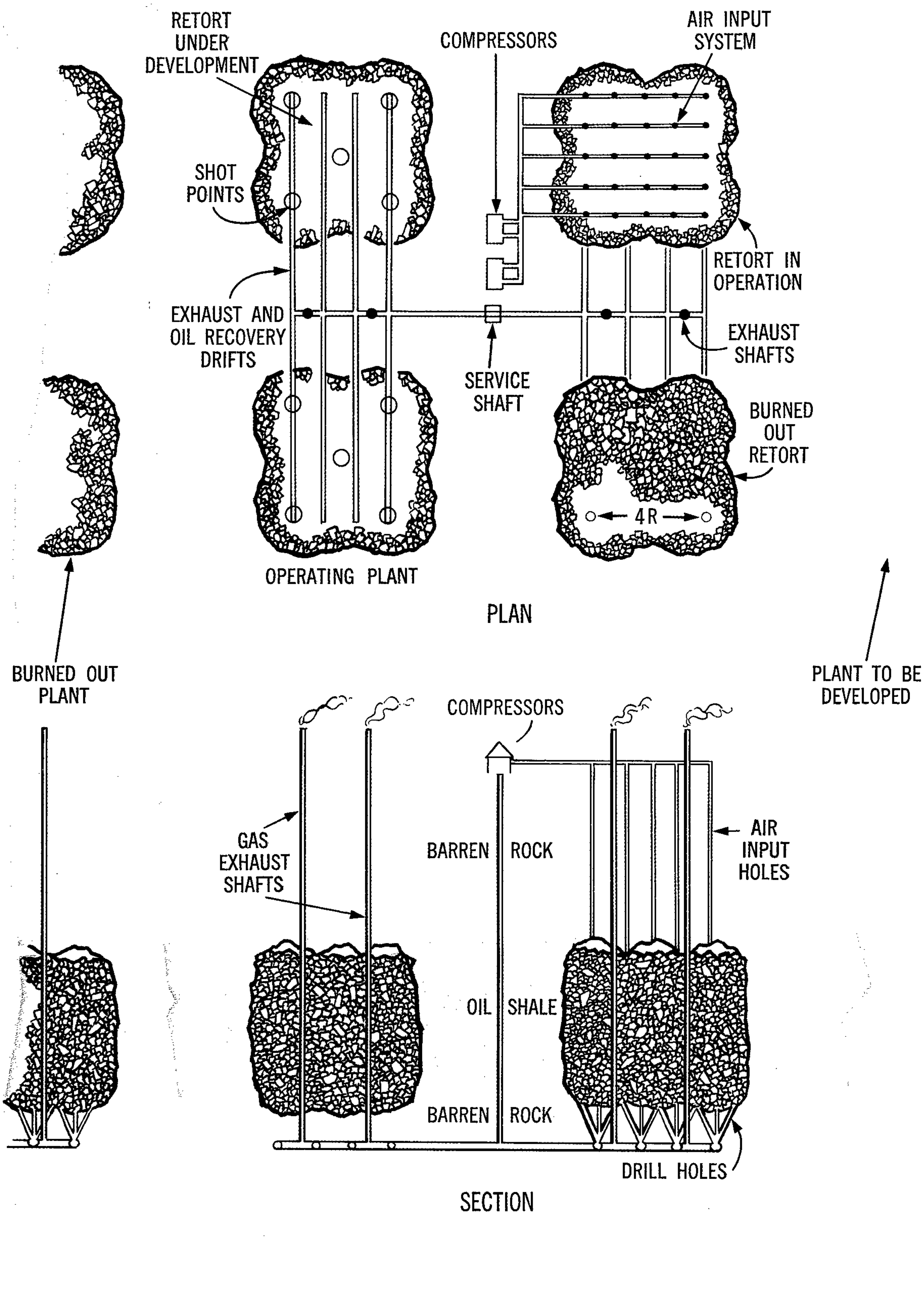


Figure 6. Concept of a commercial scale nuclear in situ retorting plant.

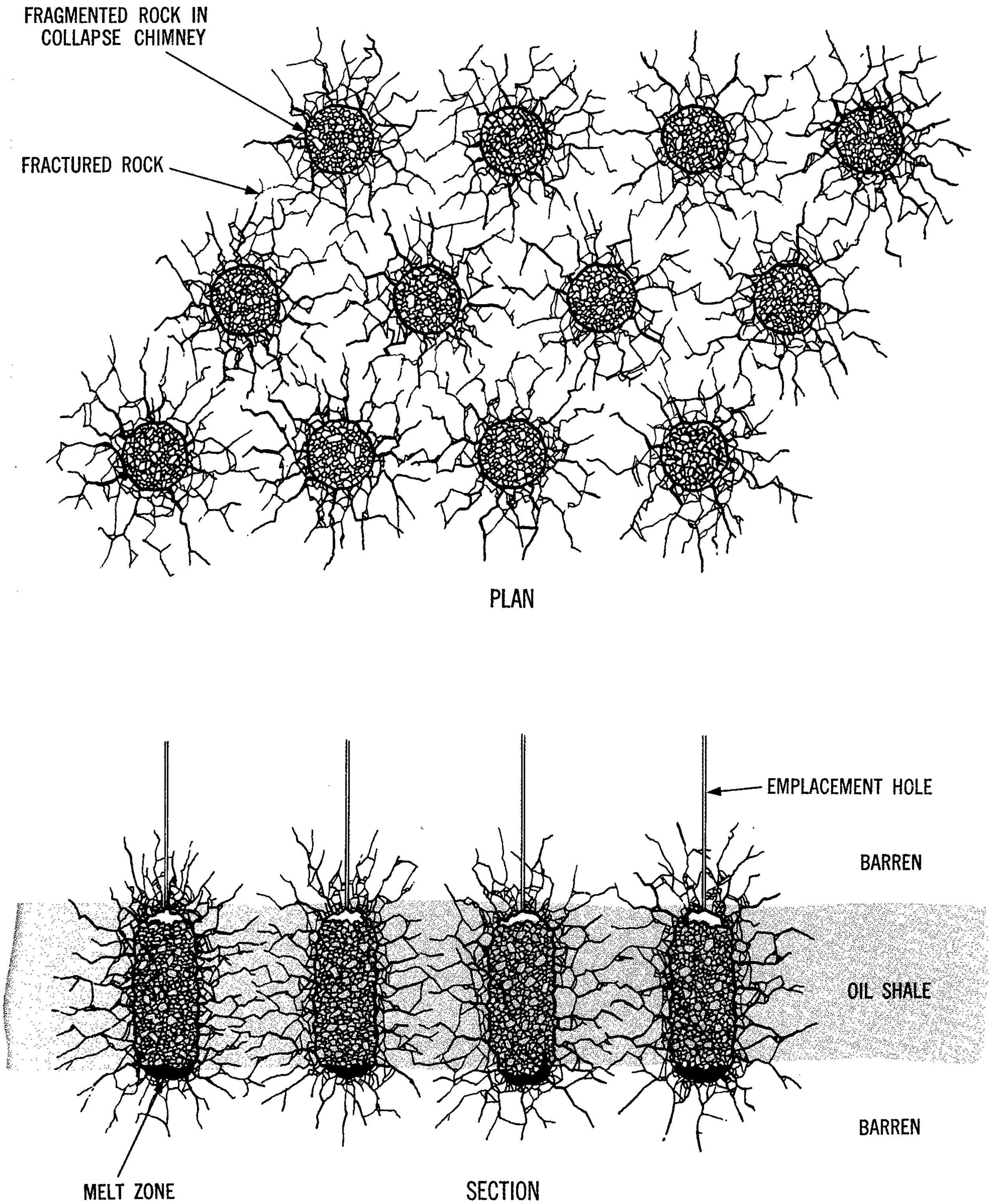


Figure 7. Array of nuclear explosions for maximum fracturing effect.

Initial information on the regional water bearing characteristics of the Green River Formation is available from the two exploratory holes drilled in the northern basin. Extensive hydrologic tests were made in these holes by the Water Resources Division of the U. S. Geological Survey. The Green River Formation can be divided, on the basis of its hydrologic characteristics, into two zones that are significant to the experiment. The Upper Zone, which extends from the surface to the bottom of the leached and fractured section (Evacuation Creek member and upper 500 feet of the Parachute Creek), and the Lower Zone, which includes the lower Parachute Creek member and the Uppermost Garden Gulch. The Upper Zone contains abundant ground water in sandstone beds of the Evacuation Creek and in the thick, permeable section of fractured and leached oil shale in the upper Parachute Creek.

The Lower Zone contains much less water, the permeability being limited to scattered fractures in the Parachute Creek and Garden Gulch members. This formation would probably produce initially less than 100 gpm into a wellbore at the site. However, pumping over a period of a few months would probably reduce the flow to about 10 gpm as the fractures in the area surrounding the wellbore are drained. The Bronco chimney and fracture system would be designed to be entirely within the Lower Zone.

The Experimental Plan

Part II of this report presents the design for an experiment for nuclear fracturing and in situ retorting of oil shale. The experimental plan envisions the drilling of a number of pre-shot exploratory holes plus an emplacement hole for the explosive. The exploratory holes would give geologic and hydrologic information about the site and would be used for the installation of instruments required for experimental measurements.

A 50 kiloton explosion would be set off at a depth of about 3,350 feet. It is expected to produce a 230-foot-diameter chimney 520 feet high, containing over one million tons of fragmented oil shale. It is expected that an annular fracture zone having a radius of up to 460 feet would surround the chimney. This fracture zone could contain as much as 18 million tons of oil shale.

Post-shot drilling would begin as soon as possible after detonation. The first hole would locate the top of the nuclear chimney and would provide information about the distribution of radioactivity underground and about fragmentation of the chimney rubble. Other holes would define the locations of the chimney edges, show the extent of fracturing outside the chimney, and expand knowledge about the distribution of radioactivity.

When the post-shot evaluation has established that further work can be safely undertaken, the oil recovery tests would begin. It is tentatively planned to conduct an in situ retorting experiment in the chimney, initiating combustion at the top and maintaining it by injection of an air-recycle gas mixture. Other recovery methods such as injection of hot reactive, and inert gases, will also be considered. Periodic temperature observations would be made at several underground locations. In addition, gas samples would be taken from several places in the underground environment during the retorting. Production wells to the bottom of the chimney and the fractured region below would be drilled for recovery of off-gas, oil mist, and liquid oil.

Subsequent to the oil recovery experiment in the chimney, an attempt would be made to recover oil from the fractured region outside the chimney. The injection of high pressure air or natural gas into the chimney would drive a combustion front outward from the chimney toward several production wells in a limited section of the fractured region. In addition to the production wells several intermediate drill holes would be instrumented to monitor progress of the recovery experiment.

Operational Safety Program

The AEC's Nevada Operations Office, which is responsible for the conduct of all AEC nuclear detonations, would review the approved field program to insure conformity to the established safety criteria. It would assume responsibility for on- and off-site safety of personnel and property. A preliminary safety evaluation is given in Appendix D.

The safety program for Project Bronco would be designed with full consideration for:

1. Damage or complaints of damage resulting from ground motion.
2. Release of effluent to the atmosphere either due to seepage through pathways in the ground or due to subsequent flushing of the chimney created.
3. Radioactive or other foreign material entering the ground water.

The procedures that would be followed to protect public health and safety for the experiment are similar to those used by the AEC in contained nuclear detonations located both on and off the Nevada Test Site (Appendix D, page 41).

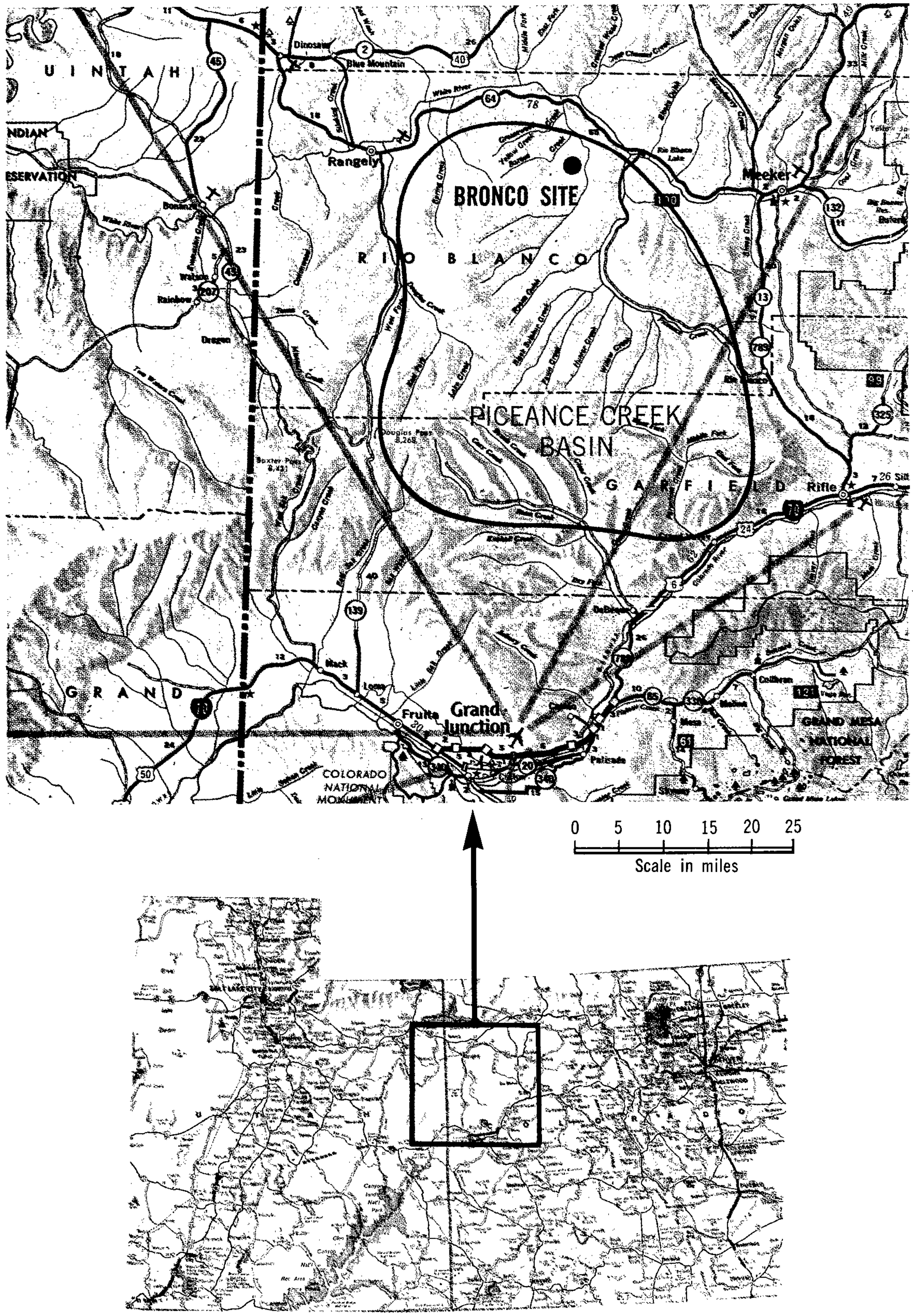


Figure 8. Regional location map, Piceance Creek Basin.

The explosive yield and location for Bronco have been carefully selected to minimize the danger of any damage from ground motion caused by the explosion. At any specific location the intensity of the movement experienced is a function of the following:

1. Energy yield of explosive.
2. Nature of rock in which explosive is emplaced.
3. Geologic characteristics of the path followed by the shock wave.
4. Nature of the surface layer on which the structure rests.
5. Distance from the explosion.

It is believed that none of the buildings in the communities surrounding the Bronco location would receive any structural damage; i.e., where the building would be structurally damaged or weakened. Pre-shot safety studies would confirm or deny this assumption.

The planned depth of the explosive that would be employed for Project Bronco is considerably greater than that which is normally required for full containment of an explosive at this yield. Based on AEC's experience with over 200 contained nuclear explosions, the release of effluent to the atmosphere from the Bronco detonation is considered remote. Although no release is expected, full safety precautions would be developed and implemented to contend with any unexpected release of radioactive material to the atmosphere. These precautions would be based on a study of the meteorology of the area and the detailed design of the nuclear emplacement.

The time of detonation would be determined by favorable weather conditions so that any conceivable release of radioactivity could be restricted to an acceptable area.

The post-shot drilling and testing programs would remain under the control of the AEC as long as is necessary to protect the health and safety of both the public and project personnel. The monitoring program would be continued during post-shot drilling to detect the presence of any radioactivity and compare with measured pre-shot levels to effect control measures if needed.

A public information program would be undertaken to acquaint state and local officials and the people in the area with the purpose and progress of the experiment and the public safety measures being developed.

Careful consideration would be given to the possibility of contaminating of local ground water supplies by solutions escaping from the chimney area (Appendix A, page 46). This is highly improbable, since the explosive would be fired at a depth where the rock formations are very impermeable, and resist transmission of water. In addition, large volumes of rock surrounding the chimney could be dewatered prior to the explosion, and maintained in that condition by pumping. Water pumped after the explosion would have little, if any contact with radioactive debris, as the withdrawal area would be outside the chimney area.

Extensive pre-shot investigations are planned to determine, in greater detail, the existing hydrologic conditions that would influence any movement of underground water.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Both the United States and the world demand for petroleum have been increasing at an accelerating rate over the past half century. Cost of discovering petroleum in the U. S. has risen steadily, and the ratio of reserves to annual consumption has been declining. To maintain adequate domestic reserves, aggressive research efforts are under way to improve technology to develop new resources to supplement conventional sources of petroleum.

The U.S. possesses tremendous reserves of oil shale. Nuclear fracturing could be the means of a major breakthrough in developing this resource. Successful development of such a method would greatly increase the recoverable reserves of oil from domestic sources to meet the nation's current and future energy requirements.

The technology of fragmenting and fracturing rocks with nuclear explosives is well developed. The technology of retorting oil shale in aboveground retorts has been under investigation for many years. This study concludes that these two technologies could be combined into an economically attractive industrial process.

An experiment is needed to provide data for further development of this concept, and to assess its technical and economic feasibility. Such an experiment could be executed without compromising public safety.

Recommendations

It is recommended that the site investigations proposed for Project Bronco be conducted to confirm the site criteria for the nuclear experiment and, if the site is found to be acceptable, to proceed with the required steps leading to a suitable project for nuclear fracturing and in situ processing of oil shale.

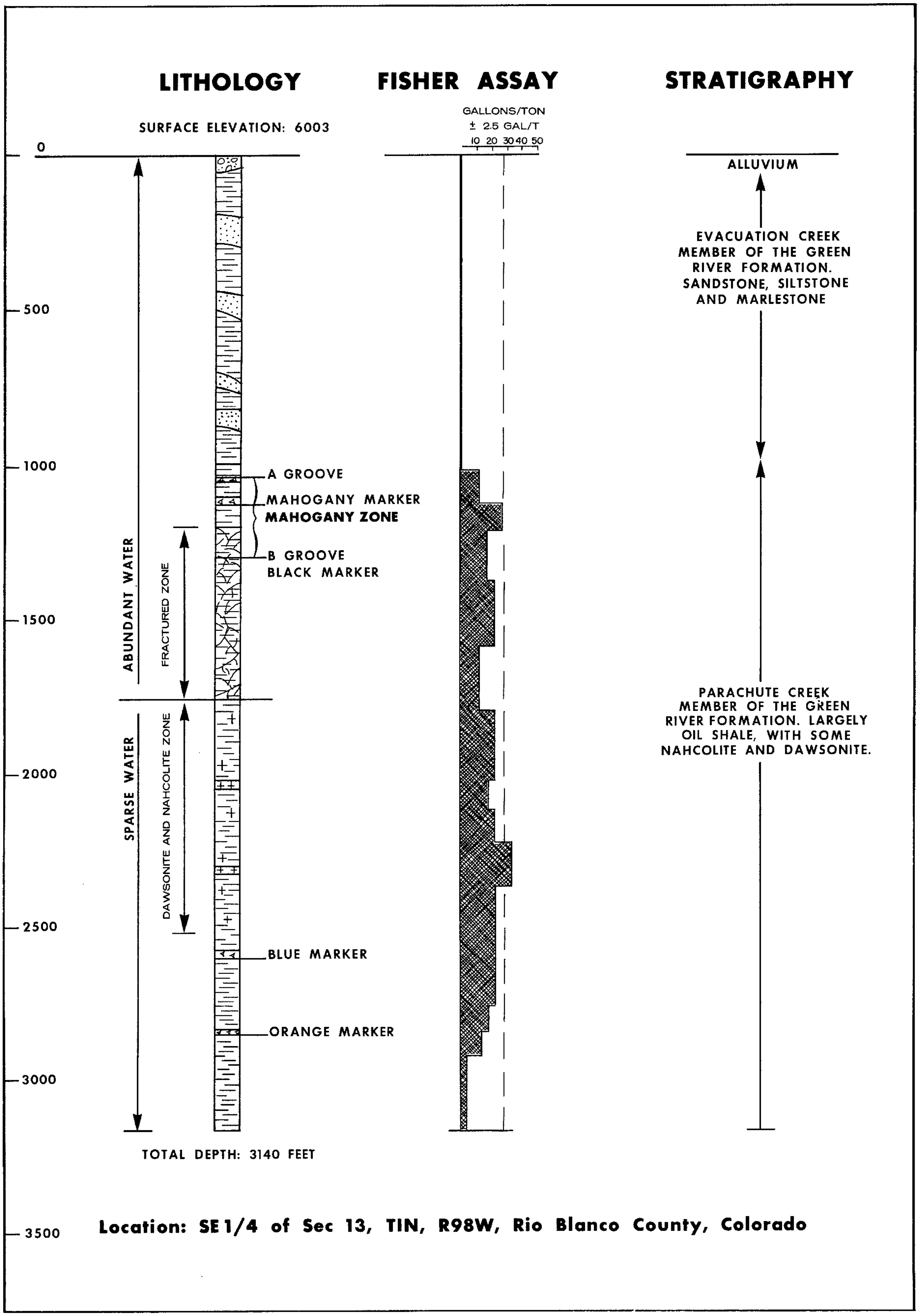


Figure 9. Geology of the USBM/AEC Corehole No. 1.

THE BRONCO OIL SHALE STUDY

Part II

A DESIGN FOR PROJECT BRONCO, AN EXPERIMENT FOR NUCLEAR FRACTURING AND IN SITU RETORTING OF OIL SHALE

by

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OBJECTIVES

Project Bronco has been designed to provide answers to several fundamental technical questions related to the recovery of oil from oil shale broken by underground nuclear explosions. The basic objectives of the experiment are:

1. To assess the technical and economic feasibility of in situ retorting as a method for recovering oil from oil shale fragmented and fractured by an underground nuclear explosion.
2. To confirm and refine the capability to predict physical properties and geometry of the cavity, chimney, and the fractured region produced by a nuclear explosion in oil shale.
3. To investigate the form and distribution of radioactivities left by the detonation and to assess their behavior during in situ retorting.

This experimental plan does not include detailed safety and security programs, detailed nuclear engineering design, or specific engineering details for measurement and control of retorting processes. It does include the major construction and equipment items and a description of the experimental program.

The design for the post-shot retorting phases is as complete as technical information will allow, but is not yet well enough defined to assure that the first objective can be attained. As further research data become available, the experimental plan will be refined. A final design can be achieved only when results of the post-shot exploration have been analyzed. No cost estimate is included in this study because of uncertainties in the final design of the retorting method.

However, knowledge gained of the fracturing and other effects of the explosion is expected to be of significant value to several potential nuclear explosion applications, independent of the design of the chimney treatment experiment.

SITE CHARACTERISTICS AND EXPLOSION EFFECTS

A committee of representatives from LRL-Livermore and various agencies of the U. S. Department of the Interior, including BuMines, has drawn up a set of technical criteria[28] for a site for a nuclear oil shale experiment. Suggestions from CER[29] and other interested parties proved helpful in the committee's deliberations.

The technical criteria include: restrictions on overburden and on oil shale thickness, grade and uniformity; restrictions on the proximity and deliverability of aquifers; restrictions on faults, fracturing, and surface zero topography; and requirements for remoteness.

Proposed Site

A subsequent search of U. S. oil shale deposits revealed a location near the S. E. corner of Section 15, T 1 N, R98W, Rio Blanco County, Colorado, which appears, on the basis of available data, to satisfy the requirements. Figure 10 is an aerial photograph of the general site area and identifies Colorado Core Hole No. 1 (CCH #1). Figure 11 is an enlargement of a portion of Figure 10 and shows tentative Project Bronco drill hole locations.

The recommended area lies about 1¾ miles west of Core Hole No. 1. A major topographic feature of the area is a locally prominent peak. A high, gently sloping plateau to the south and southwest of this peak appears to be well suited for the proposed operation. The elevation of the plateau is about 6,400 feet above sea level. The flat region is irregular in shape, and about 1,500-2,500 feet across. The plateau surface is slightly rolling, with a local relief of 20-30 feet. A few erosional streambeds which follow regional fracture patterns cut the plateau surface, but not deeply. Vegetation consists mainly of scrub cedar and sage, rooted in a thin layer of coarse soil. Approximately 1.5 miles of road construction will be necessary to provide access to the site.

Although the general area is used as cattle range in the summer, there are no active ranches within 4 miles of the site. However, White River Valley, 6 miles to the northeast contains several ranches. The nearest centers of population are Rangely and Meeker, each about 23 miles from the site. Rifle is 38 miles away, Grand Junction 80 miles.

The geology of the proposed site is given in Appendix C and the geologic fence diagram of Figure 18 summarizes the stratigraphic features from nearby drill holes.[30,37] Since the geology of the Piceance Creek Basin tends to be uniform over short distances, (Figure 2) it is presumed that this projection is reasonably accurate for the tentative site. A continuous oil shale section about 1,200 feet thick, and averaging over 20 gallons per ton is expected. The total oil shale interval, with some short barren zones, may be more than 2,000 feet thick. The bottom of the richer oil shale is estimated to occur at a depth of between 3,000 and 3,500 feet in this location.

Although a major aquifer was encountered about 1,200 to 1,300 feet above the bottom of the oil shale in Core Hole No. 1,[30] the hydrologic conditions are difficult to predict at the recommended site because, unlike the geology, hydrology in the basin may not be uniform. On the basis of hydrologic tests conducted in Core Hole No. 1 reported in Appendix C, it is expected that at least one aquifer will overlie the proposed shot point. Tests in the lower section of Core Hole No. 1 were inconclusive although they indicate some water. If the base of the upper aquifer is far enough above the shot point, and if the capacity of the lower zone is not too large, the site will be judged to be hydrologically acceptable. If, however, tests in the initial wells at the site indicate sufficient water present to interfere with an in situ retorting experiment, a new site will have to be found or de-watering of the lower zone in the area will have to be considered.

It should be emphasized that the area has not yet been formally designated as a site for Project Bronco. Should this site not prove acceptable after exploration by drill holes, an alternate site will have to be found. Two likely looking areas have been identified; both lie between the present suggested site and Yellow Creek. Should the difficulty be hydrological, it may be necessary to search for a site further removed from this area, using the original technical criteria as guidelines.

Explosion Effects

It is proposed to use a nuclear explosive of about 50 kilotons energy yield. This yield range has been selected because it is large enough so that the cavity created by the explosion will probably collapse, and small enough that only minimal effects are expected from the seismic wave generated by the explosion.

The actual depth of the explosion will be determined after a pre-shot investigation drilling program at the nominated site. The detonation point will be selected near the base of the oil shale such that the collapse chimney will be contained entirely within the oil shale sequence below the leached zone discussed in Appendix C. At this depth the chances of fracture communication between the chimney and overlying aquifers are minimized. While such communication would not contaminate any potable water supply, the inflow of large quantities of water in the chimney would complicate and add to the cost of those phases of the experiment in which recovery of oil is an objective.

For purposes of these calculations it is assumed that the depth of explosion is 3,350 feet estimated from the fence diagram of Figure 18. The scale depth of burial

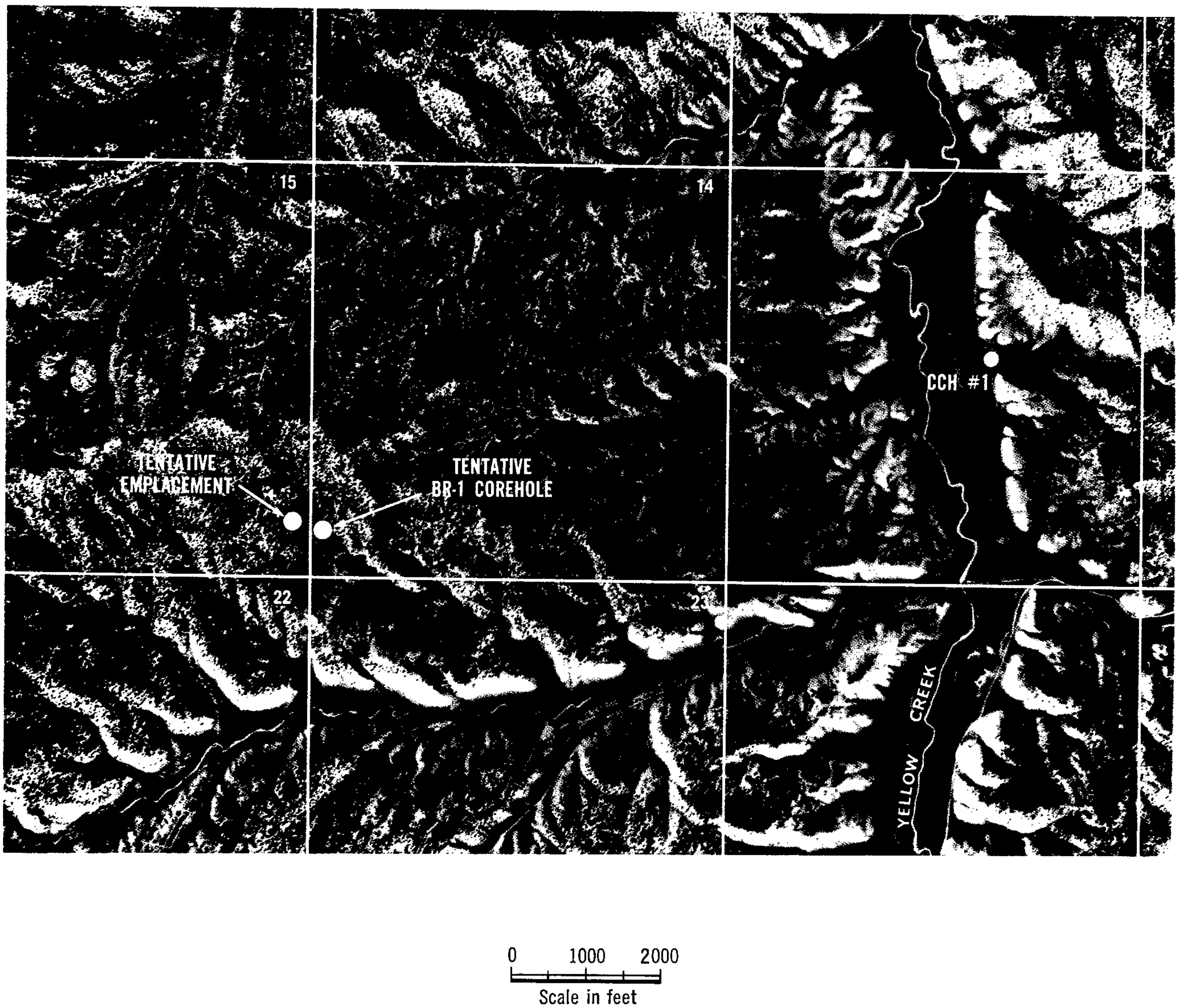


Figure 10. General Bronco Site Area — Part of T1N, R98W, Colorado.

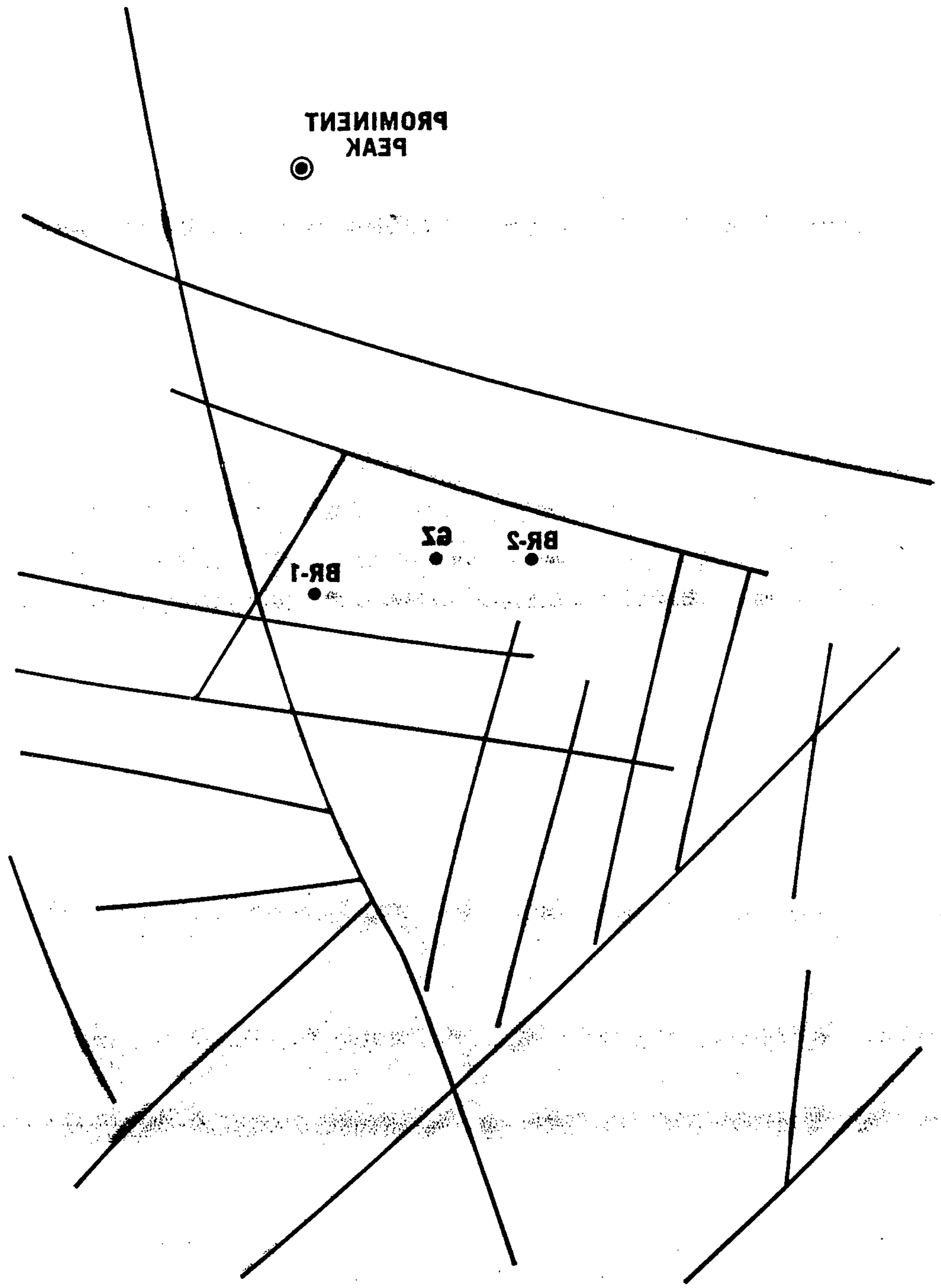

PROMINENT
PEAK
BR-1
62
BR-2

Figure 11. Tentative Bronco Site Area, showing major surface lineaments.

is 910 ft/Kt$^{1/3}$, about twice that of most explosions at the Nevada Test Site. This depth is considered more than adequate to insure containment of the explosion.

According to Higgins and Butkovich,[31] the radius of a cavity created by a contained underground nuclear explosion can be estimated by use of the expression

$$R_C = C \frac{W^{1/3}}{(\rho h)^{\alpha}}$$

R_C = cavity radius (meters)

W = explosive yield (kilotons)

ρ = average overburden specific gravity

h = depth of burial (meters)

α = adiabatic expansion coefficient, a function of water content

C = a constant; a function of rock type

In Bronco, W will be 50; h will be about 1.02×10^3; and ρ will be about 2.3. To find α, the organic material in the oil shale is assumed to behave like water during cavity expansion. Any error introduced by this assumption should not exceed the error in estimating the value of C. It is also assumed that the oil shale in the immediate vicinity of the shot point has an average grade of 18 gallons per ton.

The hydrocarbon content of this oil shale would be about 10 percent by weight[5] and, $\alpha = .298$ from Higgins and Butkovich.[31] Of the inorganic matter in oil shale, half is dolomite and half consists of feldspars, quartz, clays, etc. From the table for various rock types, C = 89 for dolomite and 103 for granite, which is rich in the silicates. The value of C for oil shale is therefore assumed to be half way between these limits, C = 96.

Thus,

$$R_C = .96 \times 10^2 \frac{(50)^{1/3}}{(2.35 \times 10^3)^{.298}}$$

$$R_C = 35.0 \text{ meters} = 115 \text{ feet.}$$

The chimney is assumed to be 4.5 cavity radii high or 158 meters (520 feet), measured up from the shot point. This is consistent with a bulk porosity of about 25% in the chimney collapse rubble. If these predictions are correct, the chimney will contain about 1.15×10^6 tons of fragmented oil shale. The surrounding fractured region will contain considerably more. The corresponding oil content of the chimney alone, assuming a 24 gallon per ton average, will be about 660,000 barrels.

Although improbable, it is possible that chimney collapse will not occur. At least one case of a standing cavity and two cases of partial collapse have been documented. In the eventuality of insufficient collapse in Bronco, the experimental plan may be expanded to include one or more attempts to induce further collapse in the oil shale overlying the cavity.

Data on which to base predictions of the extent of fractures around an underground nuclear chimney are sparse. Under some conditions, however, enhanced fracture permeability to a distance of two to four cavity radii laterally beyond the edge of the nuclear chimney has been observed.[18] In at least one case, post-shot drilling has indicated the existence of explosion-produced fractures as much as 6 cavity radii above the detonation point.[19] It is not yet clear which of several postulated mechanisms is responsible for the observed fracturing and mathematical models which predict fracturing have not yet been confirmed.

On the basis of previous experience it is estimated that the Bronco detonation will fracture as much as 460 feet laterally beyond the chimney edge and to as far as 700 feet above the shot point.

DESCRIPTION OF THE BRONCO EXPERIMENT

The Bronco Experiment is organized into four phases:

Phase I	Site Confirmation
Phase II	Construction, Detonation, and Evaluation
Phase III	Chimney Treatment
Phase IV	Fracture Zone Treatment

Breaks between phases occur at times in the project corresponding to major decision points for participants. A description of each phase follows.

Phase I. Site Confirmation

The main purposes of Phase I are to evaluate the geologic and hydrologic conditions and to establish that the site is satisfactory from technical and safety viewpoints. Three wells, BR-1, BR-1W and BR-2, will be drilled to determine the oil shale thickness, grade and uniform-

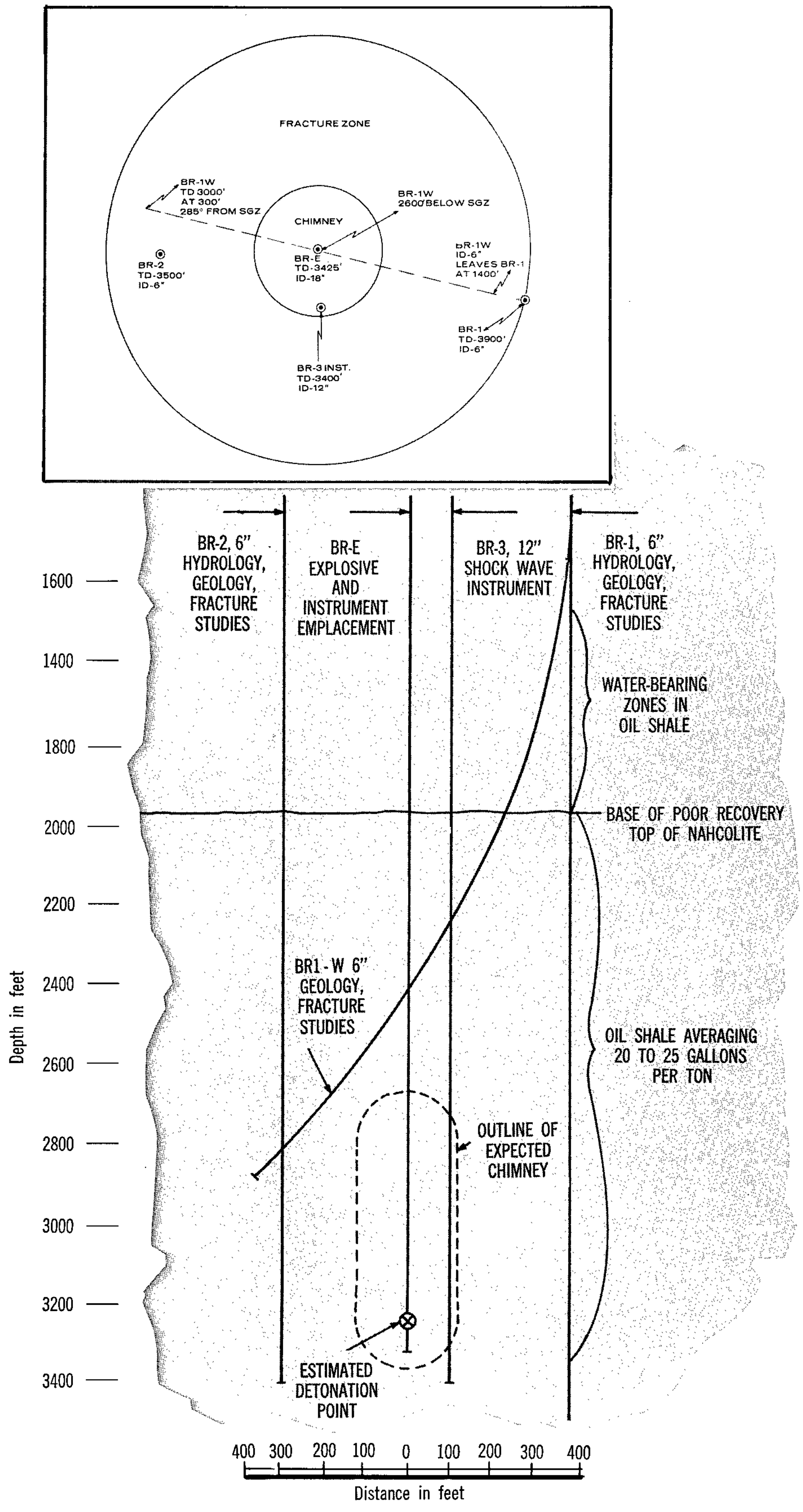


Figure 12. Phases I and IIA (Preshot) Wells.

ity; the overburden thickness; fracture occurrence and orientation; presence of other minerals; and existence and transmissibility of water zones. Locations of these wells in the tentative site area and a cross-sectional view in elevation of the wells are shown in Figure 12. The technical specifications are summarized in Table 3.

The decision by both government and industry participants regarding the technical acceptability of the site will be made after the data from BR-1, BR-2 and BR-1W are analyzed.

WELL BR-1. This will be drilled approximately 400 feet from the proposed emplacement hole location. The well will be mist drilled and cored from the Mahogany Marker (estimated ~1,480 feet) to the hole bottom of 3,900 feet. Minimum core diameter will be 3⅞ inches with maximum recovery attempted. Past experience indicates that special care will be required to recover core through the upper naturally fractured shale interval to about 2,150 feet, the estimated top of the competent shale zone. Drill stem tests will be taken of water entry zones encountered while drilling. Fluid levels, bottom hole pressure buildups and selected interval spinner tests of water zones will be taken. Fluid injection tests to determine fracture conductivity may be required. During periods that the hole is left standing, the shale member

TABLE 3—WELL SPECIFICATION FOR PHASE I SITE CONFIRMATION

	BR-1	BR-1W	BR-2
Purpose	Geologic Hydrologic	Geologic Vert. Fractures	Geologic Hydrologic
Distance from GZ	400 feet	deviated toward and beyond emplacement from BR-1	300 feet
Total Depth	3900 feet	3000 feet	3500 feet
Minimum ID	6 inches	6 inches	6 inches
Drilling Fluid	mist below casing shoe (CS)	no requirements	mist below CS
Casing and Depth	7⅝ inches at 1400 feet	re-entry of BR-1	7⅝ inches at 1400 feet
Cementing	material balance to surface		material balance to surface
Core Interval (3⅞ in.)	1450 feet to 3600 feet	300 feet total	2100 to 300 feet 2700 to 3500 feet
Logging	IES $\gamma - n$ sonic density caliper direction survey photography	IES $\gamma - n$ sonic density caliper direction survey photography	IES $\gamma - n$ sonic density caliper direction survey photography
Hydrologic Tests	swab during drilling packer flow spinner-packer flow tests to BR-2	injection packer flow spinner flow	pressure monitoring with BR-1 and BR-3
Completion	plugged to 1400 feet after tests stemmed to surface for later re-entry in BR-1R	plugged to 1400 feet with cement	instrument grouted to surface before detonation
Instruments			2 clipers (2 cables)

below the water zones should be packed off or otherwise protected to prevent recharge of possible lower permeable zones. The well will be cemented back to casing shoe after completion of the hydrologic flow-transmissibility tests between BR-1 and BR-2. A complete suite of logs will be taken.

WELL BR-2. The primary purpose of well BR-2 will be to conduct hydrologic transmissibility tests to BR-1 and possibly to BR-3, which is to be drilled as an instrument hole in Phase II-A. A second purpose is to confirm the geology at the site determined in BR-1. BR-2 is to be drilled 300 feet from the emplacement location at a point opposite to BR-1 and to a total depth of approximately 3500 feet. Final determination of depth will be on the basis of logs and core from BR-1. The hole should be cased to approximately 1,400 feet. Flow or pump tests between well BR-2 and holes BR-1 or BR-3 should help distinguish the block-joint orientation in the upper water filled zone above the competent shale zone. A 3⅞-inch core will be taken from about 2,100 to 2,300 feet to confirm the interface between the upper fractured interval and the lower competent oil shale, expected at about 2,150 feet. Core will also be taken opposite the anticipated chimney zone from 2,700 feet to 3,500 feet. Short sections of core may also be taken opposite other interesting intervals found in the BR-1 well. Complete logs will be taken in the hole.

In order to help define the fracture mechanism during the nuclear detonation, Phase II-B, a fracture cliper* gauge will be run and grouted over the entire open hole interval. In order to monitor hydraulic pressure in the major water-bearing section during and after detonation, one or more remote reading pressure gauges may be cemented in BR-2.

WELL BR-1W. The purpose of well BR-1W is to investigate the occurrence of vertical fractures or faults above the anticipated nuclear chimney. Such fractures, extending deeply into the competent shale zone from the upper aquifer system, might present hydrologic problems of post-shot communication to the chimney or safety problems related to the explosion. Subsequent to the hydrologic tests between BR-1 and BR-2, well BR-1 will be plugged back to 1,400 feet and a whipstock BR-1W started in the direction of the emplacement location. The BR-1W hole should pass over the detonation point at a depth of about 2,600 feet and will extend beyond the proposed emplacement location about 300 feet at an approximate depth of 3,000 feet. Approximately 300 feet of 3⅞-inch core will be taken. A full suite of logs will be obtained over the interval 2,000 feet to total depth. Should it appear that BR-1W has intercepted a major vertical fracture, or permeable network, tests will be made. These tests may include either injection of air or production of fluid so that the extent and capacity of the fracture interval can be estimated. The hole will be completely filled with cement shortly after testing because BR-1W is expected to pass near the fractured interval created by the explosion.

CORE ANALYSIS. Fischer Assay of approximately 1-foot intervals as indicated by lithologic examination of the core will be taken to determine the oil content. The core will also be examined for nahcolite, dawsonite and halite.

GEOPHYSICAL LOGS will at least consist of induction-electric survey, gamma neutron, sonic, density and caliper logs. Directional surveys of all wells will be required. Microseismogram or other acoustic amplitude logs will be taken for fracture and formation interpretation.

HYDROLOGIC TESTS will consist of swab tests with fluid level and pressure build-up measurements while drilling. Subsequent to drilling, pump tests for extended periods will be made to determine transmissibility and capacity of the zones. Packed zone spinner surveys, pressure drawdown and build-up analysis of flow capacity will be made in tests of individual wells. Constant rate pumping from one well while monitoring with down-hole instrumentation will be done for between-well tests.

FRACTURE STUDIES will be conducted in pre-shot and post-shot holes. These studies may involve the use of borehole photography, spinner-monitored air or gas injection and impression packers.

Phase II. Construction, Detonation and Evaluation

Once the tentative Bronco site has been shown to satisfy the geologic, hydrologic, and safety criteria, the major construction for nuclear experiment will begin. Plans for Phase II call for:

1. Drilling an instrument hole (BR-3) and an emplacement hole (BR-E).
2. Installing instrumentation required for scientific measurements and safety documentation.
3. Emplacing and detonating the nuclear explosive.
4. Re-entering the explosion environment, evaluating any hazardous conditions, and establishing appro-

*Down-hole coaxial cable providing open circuit at fracture. Time record of electrical length of severed cable defines depth of occurrence of horizontal fractures. May be used to monitor chimney collapses.

priate safety procedures for the remainder of the experiment.

5. Investigating the nuclear chimney and fractured zones in preparation for subsequent in situ treatment. Measurements will be made of the chimney dimensions, rubble size distribution and void volume; radioactivity levels, species and mode of occurrence; temperature and pressure levels; fracture extent, fracture density, and permeability.

Data from Phase II will allow a more definitive design for the treatment phases of the experiment. Specific well locations in the post-shot program may be changed as a result of data obtained on preceding wells.

The description of Phase II is further divided into three subphases:

Subphase II-A	Pre-shot Construction
Subphase II-B	Detonation
Subphase II-C	Evaluation

Subphase II-A. Construction

In addition to normal site construction of roads, trailer pads, etc., two wells, BR-3 and BR-E, are required. Well locations are shown in Figure 12. Specifications for the wells are given in Table 4.

WELL BR-3 will be drilled 100 feet from the emplacement location. Although its primary purpose is that of an instrument hole for monitoring and recording explosion-associated phenomena, it will afford an additional opportunity for coring or testing of the formations if deemed advisable after examination of Phase I data.

BR-3 will be a 12-inch minimum inside diameter well with 13⅜-inch casing through the upper water zones to approximately 2,300 feet, and to a total depth of about 3,400 feet. Oil shale intervals previously missed, or intervals of interest determined from wells BR-1 and BR-2, will be cored. Wet hole logs will be taken over the entire well. Hydrologic tests in BR-3 with pressure monitoring in well BR-2 may be desirable while drilling, although extensive testing is not planned.

WELL BR-E, the emplacement well, will be drilled to a total depth of 3,425 feet and sized to take an explosive at least 18 inches in diameter. The well is to be cased below the surface waters but no specific deeper casing requirements are necessary since the well will be appropriately stemmed and will not be re-entered after the shot. The nuclear explosive will be emplaced in mud and the hole stemmed to surface. Logs will be taken in the well for correlation purposes. The specific shot depth will be determined from the logs and correlative data from BR-1 and BR-2.

GENERAL CONSTRUCTION. All-weather access roads, trailer pads, and the control point (CP) and recording trailer park (RTP) will be constructed during Phase II-A for primary occupancy during Phase II-B. The surface topography of the entire area is such that numerous sites for CP and RTP exist with a minimum of clearing and leveling.

Communication facilities will be constructed from existing telephone service to the CP and ground zero (GZ) locations. Cable-ways for shot-associated instrumentation and firing will be graded from the BR-E, BR-3 and BR-2 wells to the CP and RTP areas.

A building near GZ is required for final explosive assembly and checkout. Fencing and guard houses are needed at GZ and the CP.

Subphase II-B. Detonation

The Atomic Energy Commission will have the responsibility for the safety program associated with the nuclear explosion. Weather studies, radioactivity monitoring, and seismic measurements will be essential elements of the safety program. Specifications for wells to be drilled in this subphase are given in Table 4. The well locations are shown in Figure 13.

Dynamic motion sensors will be loaded into holes BR-3 and BR-2 and cemented to surface. Hole BR-3 will be fitted with a string of peak pressure gauges, stress history transducers and velocity slifers* to give data on the variation of shock wave characteristics with distance and time. The emplacement hole, BR-E, will also contain similar gauges in addition to cavity collapse detection instruments. Fracture cliper instrumentation will be cemented in BR-2.

The explosive will be transported to the site and emplaced in BR-E with its associated instrumentation. The well will be stemmed, i.e., backfilled, for full containment in a manner based on previous experience. The cementing in the pre-shot holes will be conducted with strict material balance control, including caliper surveys, to insure that no channels exist for radioactivity to escape during the explosion and also to insure a low

*A slifer is a coaxial cable arranged more or less radially to the detonation point. The advancing shock wave generated by the explosion crushes the cable. Electronic instrumentation continuously measures its electrical length, i.e., the length of unshorted cable. Analysis of the data gives shock front position as a function of time.

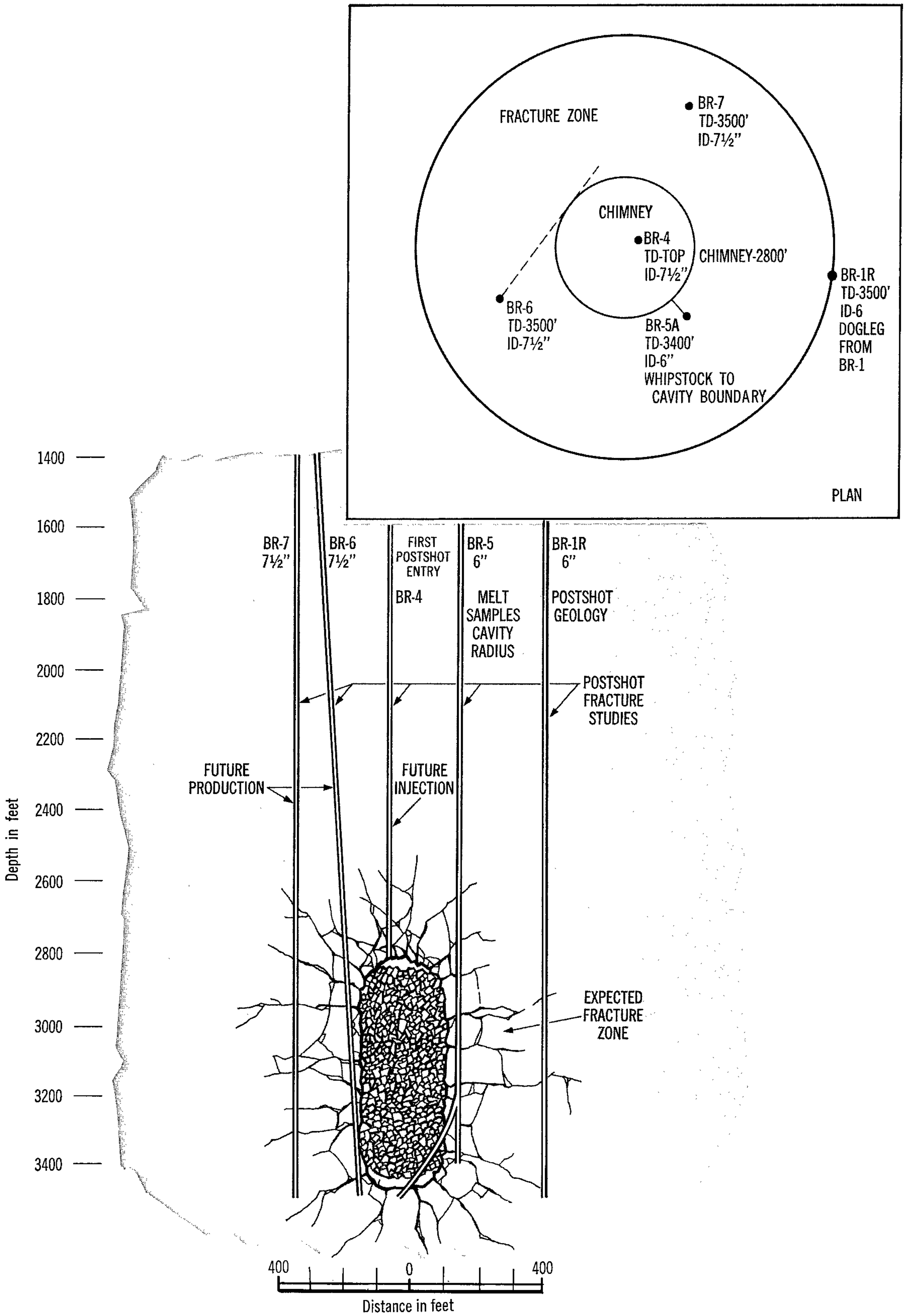


Figure 13. Phases II-B and II-C Wells.

TABLE 4—WELL SPECIFICATIONS FOR PHASES II-A AND II-B

	BR-3	BR-E	BR-4	BR-5
Purpose	Instrument	Emplacement	Chimney Re-entry, Injection	Radiation Samples and Production
Distance from GZ	100 feet	0 feet	25 feet	160 feet
Total Depth	3400 feet	3425 feet	to chimney top, ~2800 feet	3400 feet whipstock from 3200 to 3500 feet
Minimum ID	12 inches	>18 inches	9⅝ inches below CS	6 inches
Drilling Fluid	mud	mud	mud to CS gas below CS	mud to CS gas below CS
Casing Size & Depth	13⅜ inches to 2300 feet	20-inch conductor to 400 feet	13⅜ inches to 2300 feet	7⅝ inches to 2300 feet
Cementing	material balance to surface		to surface	to surface
Cores (3⅞ in.)	approx. 200 feet	none	2300 feet to chimney	2300 feet to TD whipstock
Logging	IES γ-n sonic direction survey caliper	IES γ-n sonic direction survey density caliper	γ-n temperature radiation direction survey caliper	γ-n temperature radiation direction survey caliper
Testing	swabbing while monitoring BR-2	to pass a mandrel	gas samples photograph pressure up	gas samples photograph flow from chimney
Completion	instrument loaded—grouted to surface	load explosive and stem to surface	recompleted injection well for Phase III	recompleted for post-treatment coring in Phase III and as production well in Phase IV
Instrumentation	2 peak pressure 3-3 component stress gauges 6 time of arrival switches (12 cables)	2 peak pressure 3 cliper 2 slifer (9 cables)		

probability of communication between overlying water zones and the nuclear chimney.

Weather will be monitored for the event even though the possibility of any release of effluent material above the ground surface is extremely remote. Postponement of the explosion will occur if conditions are unfavorable. Ground surface motion will be measured at several locations within a few miles of surface zero. Seismic motion will be measured at selected ranches and nearby population centers.

WELL NO. BR-4 will be the first re-entry well into the top of the chimney; drilling will start as soon as possible after the shot. The well will be located 25 feet from the emplacement location BR-E. It will also be used later as an injection well in Phase III. Therefore, the drilling program will be: cement 18-inch conductor pipe to surface through surface waters; drill with mud through the upper, naturally fractured water-bearing zones and into the top of the competent shale zone at about 2,200 feet; cement 13⅜-inch casing into the competent shale zone to about 2,300 feet; change over to gas or mist drilling below 2,300 feet, taking 3⅞-inch core from the casing shoe to the top of the chimney. Care will be taken to insure maximum core recovery.

Pressure, temperature, and radioactivity measurements will be made during drilling. Logs and temperature surveys together with downhole photography will help determine the height of the explosion-created fractured interval above the chimney. The hole will be used for taking early samples of the chimney gas for chemical and radioactivity analyses. Photographic studies of the top of the chimney rubble will help define rubble size distribution. Chimney volume and wall rock average permeability will be measured by gas injection and pressure fall-off techniques.

WELL NO. BR-5 will be drilled parallel to the chimney wall about 160 feet from the emplacement location. The exact distance will depend upon the approximate radius of the chimney determined by the pressure experiments in BR-4. The well will be cased with 9⅝-inch casing into the competent shale member below the water and inert gas cored from that depth to a total depth of 3,400 feet. During drilling gas samples will be taken every 100 feet opposite the chimney interval. The samples will provide radioactivity values at various levels in the chimney in communication through fractures to the well bore. Complete dry hole logs will be taken. Downhole impression blocks, packer spinner runs, photography or television may be used to assist in determination of fractured intervals. A drillable plug will be inserted at approximately 3,200 feet and a whipstock made to intersect the chimney wall at the approximate detonation level. This whipstock will be used to define the chimney boundary and also will be continued through the bottom of the chimney to obtain melt samples for explosive performance studies.

RADIOACTIVITY. The gas, fluid, and core specimens taken in Phase II-B will be used in the radioactivity study. In addition, it may be desirable to flush the chimney by injecting inert gas into BR-4 and flaring (if safe) the return gas from BR-5. If levels of radioactivity are too high, the flaring experiment may be postponed until Phase III.

Radiation measurements made during post-shot drilling will assess the nuclear chimney environment and assist in planning subsequent safety programs. During Phase II-B the site will be strictly monitored for radioactivity levels. Blowout preventers will be used and positive control of drill cuttings and return gas will be maintained. Radioactive cuttings will be recovered for analysis and disposal; return gas may be highly diluted and stack flared. A high pressure gas recirculation system will be employed. Oxygen will not be admitted to the system or the chimney.

A delay to allow for radioactive decay may be indicated. The remaining post-shot environment investigation wells in Phase II-C will not be drilled until the radiation problem has been assessed from BR-4 and BR-5.

PRECAUTIONS WITH BR-4 AND BR-5. Care will be taken with both wells to insure that the upper water zones are cased off so that communication and subsequent flooding of the chimney is prevented. The chimney and fractured zone should be kept dry if possible to prevent subsequent problems with the treating Phases III and IV. Testing of the hydrology in the upper interval will not be necessary although pressure levels in the zone should be measured while drilling to determine whether there is apparent communication with the chimney.

Subphase II-C. Evaluation

The intent of this post-shot program is to perform a thorough evaluation of the nuclear chimney-fractured area complex to determine whether an in situ treatment can be carried out.

Three holes, BR-1R, BR-6 and BR-7, will be drilled to establish the nature and extent of fracturing surrounding the chimney. In addition to being used in investigating the fracture system, they will later become a part of the oil recovery phases. Specifications for the

wells are given in Table 5. The relative locations of the wells are shown in Figure 13.

WELL BR-1R will be a re-entry of BR-1 with deviation at about 1,400 feet. A 3⅞-inch core will be taken to a total depth of 3,500 feet. Complete geophysical logs will be taken. The object is to compare BR-1R information with the pre-shot cores and logs taken at the same location in BR-1.

WELL BR-6 will be a new well located 250 feet from the emplacement hole. Although its primary purpose is fracture investigation outside the chimney, it will be cased with 13⅜-inch casing into the competent shale zone below the natural water system such that it can be enlarged during the Phase III chimney treatment for use as a production well. It is to be inert gas drilled, cored below the casing to 3,500 feet and slanted to graze the cavity radius near the base of the chimney on the northwest side. Complete logs will be taken and downhole tests will be made in the well to study fractures. These tests may include injection spinner runs with packers, photography, and impression packers.

WELL BR-7 will be a straight well located 300 feet from the emplacement location opposite BR-6. Like BR-6, it will be cased into the competent shale zone with 13⅜-inch casing for future use in Phase III as a production well. Core and logs will be taken and tests will be made in the straight hole for fracture location, fracture density and permeability determinations. On completion of these tests the straight hole will be plugged back so that a larger slant hole can be drilled into the base of the chimney and completed as a production well in Phase III.

Fracture studies in all post-shot holes will include examination of the core and geophysical logs, downhole photography, the impression packer where indicated and gas injection with packer-spinner gauge. Directional surveys will be taken in all wells to determine geometry of the induced fracture system. Post-shot cores will be examined for fractures bearing radioactive material. Analysis of such fractures may help to reveal at what time they developed during cavity and chimney formation. This information will help to indicate whether the fractures were caused by the outgoing shock wave, by the collapse which formed the chimney, or by subsequent relaxation and stress adjustment in the medium. When the mechanisms are more clearly understood, better fracture prediction will be possible.

TABLE 5—WELL SPECIFICATIONS FOR PHASE II-C

	BR-1	BR-6	BR-7
Purpose	Core-fracture	Fracture, Production	Fracture, Production
Distance from GZ	400 feet	250 feet	300 feet
Total Depth	3500 feet	3500 feet	3500 feet
Minimum ID	6 inches	7⅞ inches	7⅞ inches
Drilling Fluid	gas	gas	gas
Casing size and depth	existing BR-1	13⅜ inches to 2300 feet	13⅜ inches to 2300 feet
Cementing	-----	to surface	to surface
Cores (3⅞ in. dia.)	2300 to 3500 feet	CS to 3500 feet	CS to 3500 feet
Logging	γ-n density temperature deviation survey	γ-n density temperature deviation survey	γ-n density temperature deviation survey
Testing	injection pressure monitoring spinner	impression block injection spinner photography	impression block injection spinner photography
Completion	open hole packer and tubing below water	recompleted in Phase III for production	recompleted in Phase III for production

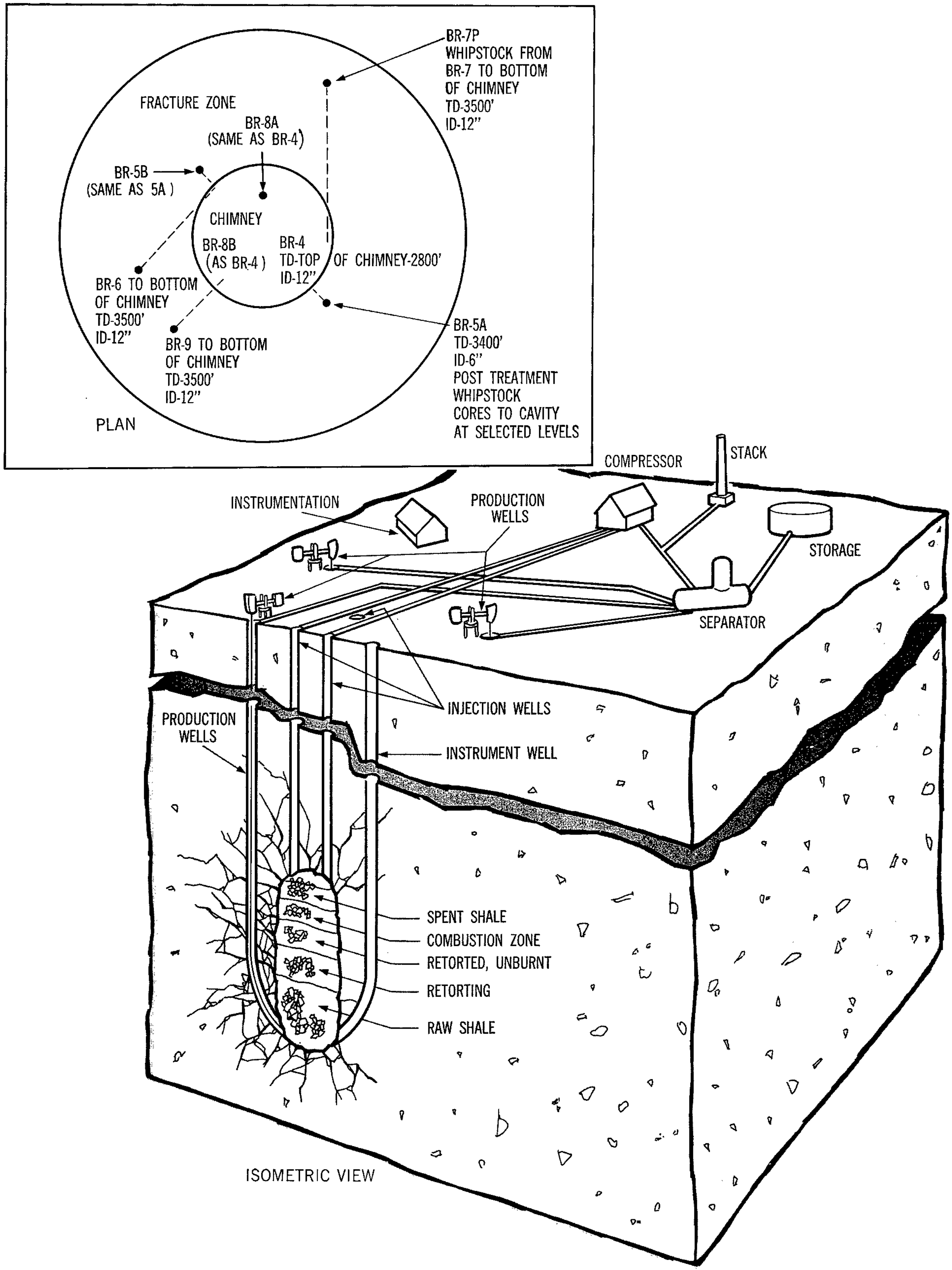


Figure 14. Phase III Wells.

Phase III. Chimney Treatment

Phase III consists of a full-scale experimental treatment of the oil shale rubble in the chimney. Its purpose is to assess the technical and economic feasibility of the method or methods chosen by measurement of process parameters and by examination of the products. The following key questions will be asked in this phase: What proportion of the potential shale oil can be recovered? Is there radioactivity in the product oil? If so, what is its distribution? What are the effects of important control variables such as air recycle gas ratio upon measured results such as temperature distribution and gas composition?

The preliminary Phase III design is based on retorting with the heat generated by combustion of the carbonaceous residue in retorted oil shale.

This design will probably be modified prior to the execution of Phase III as more technical information becomes available from BuMines retorting experiments, from theoretical studies of the retorting process, and from prior Bronco investigations. Furthermore, industrial research on other retorting methods, including the use of preheated inert or reactive gas (without in situ combustion) may suggest the testing of one of these techniques in Bronco. In this present definition of the experiment it is assumed that:

1. The chimney dimensions are 115 feet radius and 520 feet high.
2. The grade distribution of oil shale in the chimney is the same as that in Core Hole #1. (See Figure 9 and Figure 18.)
3. No pressure problems are present other than those associated with fluid flow. The chimney exists as a closed retort and there is no uncontrollable inflow of water.
4. The technique of in situ combustion of residual coke in spent shale is used following an initial period in which hot natural or combustion gases are injected to pre-heat the top of the bed. After this pre-heating, air will be injected with or without natural gas to attempt uniform ignition over the bed. The design includes the option of recirculating a fraction of the off-gas.
5. The experimental data on retorting front advance rates and air volume requirements, accumulated by the Bureau of Mines at Laramie in retorting unsorted mine run shale up to 20 inches in two dimensions, are applicable in scaling to the nuclear chimney. This scale up factor is approximately 10^5 on a total volume basis.

The foregoing assumptions imply that the chimney will contain about 1.15×10^6 tons of oil shale. However, some oil shale in the chimney wall will be retorted as well. Thus for the purpose of making retorting calculations, it is assumed that the retorting will affect 1.3×10^6 tons of oil shale at an average grade of 24 gallons per ton containing about 3.1×10^7 gallons of shale oil of which 80 percent may be recoverable. This is equivalent to a recovery of 2.5×10^7 gallons or 5.9×10^5 barrels of shale oil.

Analysis of data from the BuMines 10-ton retort suggests that an average downward advance of the retorting front in the nuclear chimney could be as low as 1.5 feet per day. At this rate, a year would be needed to treat the 520-foot Bronco chimney. Extrapolation of data from the retort indicates that an air injection rate of per day. At this rate, a year would be needed to treat oil shale. With the use of recycle gas, the total flow requirement would be about 18,000 scf per ton.

The Bronco chimney is expected to be thermodynamically more efficient than the Laramie retort. The latter leaves about one-third of the heat generated by combustion in the 1000°F spent shale at the conclusion of retorting. The corresponding spent shale temperature in Bronco is expected to be closer to 400°F, since the input gas temperature from the compressor is estimated to be about 310°F. The requirement for heat – and thus for air – in Bronco would be reduced. For design purposes, an air requirement of 8,250 scf/ton and an air-plus-recycle-gas requirement of 13,500 scf/ton is assumed. A total of 1.75×10^{10} scf of air and gas will be needed. The average daily rate will be 4.9×10^7 scf for 360 days.

If all the oil is produced as a liquid, and if 80 percent recovery is assumed, the average daily pumping rate will be about 1,650 barrels/day.

To provide for the necessary gas flow at a pressure drop of a few atmospheres requires three injection wells and three production wells, each with a minimum ID of 12 inches. The locations of these wells are shown in Figure 14, the specifications are shown in Table 6. To provide this,

1. The open hole section of hole BR-4 will be enlarged to a minimum ID of 12 inches to the top of the chimney for use as a gas injection well.
2. New holes, BR-8A and BR-8B, will be located about 75 feet from GZ and spaced equally about GZ from BR-4. These holes will be additional in-

jection wells and will be drilled with mud to about 2,300 feet, with 13⅜-inch casing set into the competent shale. The wells will be gas drilled further to the top of the chimney at about 2,800 feet, with a minimum ID of 12 inches.

3. Although drilling at the Nevada Test Site into loose, unsorted, widely varying size blocks contained in chimney rubble zones has been difficult and oftentimes costly, an attempt will be made to place 3½-inch OD drill strings in the rubble to the bottom of the chimney in the injection wells BR-4, BR-8A, and BR-8B. The purpose of these strings would be to provide channels to periodically monitor process variables in the retort bed.

4. Hole BR-6 will be enlarged to a minimum ID of 12 inches and extended into the bottom of the chimney.

5. A new hole, BR-9, will be located about 250 feet from GZ and will be slanted to the bottom of the chimney. It will be completed to 2,300 feet with 13⅜-inch casing cemented to the surface. Below 2,300 feet it will be drilled with a minimum ID of 12 inches.

6. Hole BR-7, having been plugged back to the casing shoe, will provide access for a whipstock hole, BR-7P, with a minimum ID of 12 inches slanted to enter the bottom of the chimney.

7. Each of the holes, BR-6, BR-7P and BR-9, will be a production well. A string of 3½-inch OD tubing and a down-hole pump will be inserted in each for use in recovery of liquid shale oil and water. Retort gases will be produced through the annuli of these wells. In the event that additional production capacity is required, Well BR-5 can be similarly equipped in Phase III.

8. The outputs of BR-6, BR-7P and BR-9 will be monitored for radioactivity and chemical composition with automatic equipment. Sufficient equipment will be provided so that the effluent of the three production wells can be processed collectively on line to separate the oil, water and gas phases. Provision will be made for bleeding a fraction of the off-gas to the intake of the compressor system for recycle.

9. A compressor system will be installed to force gases under pressure into the chimney. It is assumed that the permeability of the chimney itself will be sufficiently great that the pressure drop due to gas flow is small compared with the pressure drop in the injection and production wells. At the postulated injection flow rate, shared equally by the triple system of wells, it is calculated that the pressure drop through the injection wells will be about 15 PSI and through the production wells about 31 PSI. Allowing 6 PSI for pressure drop across the chimney and in flaring and at an ambient pressure of 12 PSIA for the 6,400-foot elevation, the input pressure to the injection wells must be about 63 PSIA. Operating at a pressure in this range at high flow rates, the use of centrifugal compressors is indicated. The power requirement to maintain the expected flow at the pressure ratio required is calculated to be about 6,000 brake horsepower. This value is based on use of two multistage compressors in tandem, each at a pressure ratio of 2.345, with inter-cooling to a temperature of 100°F between compressors. The gas temperature at the injection wells then becomes about 310°F.

10. Aboveground storage will be required for product oil and water. It is proposed to provide on-site tank storage, in increments of 10,000 barrels, for up to 50,000 barrels for storage of contaminated oil. This volume corresponds to the maximum amount of oil which could result from the heat of the explosion.[24] As stated in Appendix B, the Bronco experiment is required to determine the amount, degree and mechanism of oil contamination. Consideration will be given to using this oil as fuel to supply part of the heat required during phase IV. If this is undesirable, the oil could be returned to the chimney at the conclusion of the experiment. In addition, temporary storage capacity of not more than 20,000 barrels should be provided for disposable oil. Furthermore, temporary storage aboveground of about 1,000 barrels, should be provided for the saline water effluent of the separation stage. Consideration will be given to reinjection of this water into a saline-water bearing formation continuously during the experiment. For this purpose, hole BR-1R could be used by insertion of a packer at a suitable depth and the casing perforated over a sufficient interval to handle the volume required.

11. At the conclusion of the chimney treatment period, Wells BR-5A and BR-5B will be re-entered to provide core samples into the chimney walls at selected levels, suggested here to be evenly spaced at quarter-chimney heights. Wells BR-5A and BR-5B are tentatively located 40 feet outside the chimney on opposite sides. Analysis of the cores will

TABLE 6 — WELL SPECIFICATIONS FOR PHASE III

	BR-4	BR-5A BR-5B	BR-6
Purpose	Injection and Temperature Survey	Post-treatment Survey near Chimney	Production
Distance from GZ	25 feet	~160 feet	250 feet
Total Depth	2800 feet	various	3500 feet
Minimum ID	12 inches	6 inches	12 inches
Drilling Fluid	gas	mud to CS gas below CS	gas
Casing Size and Depth	existing	existing BR-5 for BR-5A – 7⅝ inches to 2300 feet for BR-5B	existing
Tubing or Drill Pipe	3-inch pipe to 3500 feet	–––––	3-inch tubing to 3500 feet
Cement	to surface	to surface	to surface
Core (3⅞ in. dia.)	none	whipstock into chimney at selected levels	none
Logging	none	direction survey radioactivity survey	direction survey
Hydrologic Tests	none	none	none
Completion	injection plus drill pipe for surveys	BR-5A recompleted as production well in Phase IV	production with tubing and liquid pump

	BR-7P	BR-8A BR-8B	BR-9
Purpose	Production	Injection and Temperature Survey	Production
Distance from GZ	300 feet	75 feet	250 feet
Total Depth	3500 feet	2800 feet	3500 feet
Minimum ID	12 inches	12 inches	12 inches
Drilling Fluid	gas	gas	gas
Casing size and depth	existing	13⅜ inches to 2300 feet	13⅜ inches to 2300 feet
Tubing or Drill Pipe	3-inch tubing to 3500 feet	3½-inch pipe to 3500 feet	3-inch tubing to 3500 feet
Cement	to surface	to surface	to surface
Core (3⅞ in. dia.)	none	none	none
Logging	γ-n caliper direction survey temperature	γ-n caliper direction survey temperature	γ-n caliper direction survey temperature
Hydrologic Tests	none	none	none
Completion	production with tubing and liquid pump	injection plus drill pipe for surveys	production with tubing and liquid pump

provide data on the extent to which the treatment of the chimney has effectively retorted the shale beyond the chimney walls.

Phase IV. Fracture Zone Treatment

The purpose of Phase IV is to conduct an experimental in situ treatment of a selected sector of the fractured zone surrounding the chimney. The data will provide a basis for determining the technical and economic feasibility of extending in situ treatment beyond the chimney and for predicting the optimum spacing of multiple nuclear chimneys for a full-scale basin development program. The key questions to be answered are: To what extent does the fracture system remain open? What proportion of the shale oil potential can be recovered? To what distance? Is radioactivity a problem in the fracture zone?

As in Phase III the basic technical problems will not be identified until after the post-shot evaluation; indeed, they may not be fully identified until after the treatment of the chimney rubble has been completed. While it is predicted that the oil shale will be fractured out as far as 460 feet by the nuclear explosion and expected that this fractured zone will exist at the outset of the chimney treatment, it is by no means certain that the fractured zone will still exist, in full or in part, at the time the treatment of the chimney is completed. It is entirely possible that the overburden pressure will have resulted in sufficient plastic flow to seal off a substantial portion of the fractured zone. The U.S. Bureau of Mines in Laramie is conducting a laboratory investigation of the effect of pressure on oil shale of various grades. The results of this effort are desirable to improve the capability to predict the behavior of the fractured zone under overburden pressure.

For the purpose of present planning, it is assumed that sufficient permeability will exist in at least a portion of the fractured zone and that it can be maintained sufficiently long to conduct a meaningful experiment. As in Phase III, the technical guidance committee will be faced with a choice of treatment method. The principal choices appear to be:

1. In situ combustion of residual coke with ignition over a segment of the chimney walls, possibly including further combustion of coke in the chimney rubble, with peripheral production wells.

2. In situ combustion commencing at peripheral injection wells with production from the same chimney wells as in Phase III.

3. Aboveground combustion of natural gas at high pressure and injection of combustion gases into the chimney or into peripheral injection wells.

4. Aboveground heating at high pressure of a mixture of gases in the absence of oxygen and injection either into the chimney or into a set of peripheral wells.

For project planning purposes, it is assumed that:

1. The first of the technical approaches listed above is selected.

2. The air and recycle rates per ton of oil shale treated which were applicable to Phase III are also applicable to Phase IV.

3. The effects of the explosion are as predicted.

4. The oil shale grade data obtained from Core Hole No. 1 are applicable to the fractured zone.

It is proposed to confine the in situ treatment experiment to a 45° sector of the fractured zone and to investigate the efficacy of the treatment out to a radius of about 200 feet or 80 feet from the edge of the chimney. This sector of the fractured zone contains about one-fourth as much oil shale as does the chimney. Hence, treatment might be accomplished in about one year with about one-fourth the daily air rate required in Phase III.

The locations of additional wells for the fracture retorting experiments are shown in Figure 15, the detailed well specifications are shown in Table 7; and a schematic concept for the fracture zone treatment is given in Figure 15. These requirements are:

1. Hole BR-5 will be used as one of the first set of production wells. Prior to drilling the remainder of the set, pressure and flow tests will be conducted between one of the chimney injection wells, e.g., BR-4 and BR-5, to use in predicting compressor and horsepower requirements.

2. New holes, BR-10A and BR-10B, will be drilled to a depth of 3,400 feet at a distance of about 40 feet outside the wall of the chimney. The exact distance will depend upon the extent to which retorting into the chimney walls is revealed by analysis of cores taken from wells BR-5A and BR-5B. If it is found that insufficient permeability exists between the chimney and the production wells, it may be desirable to attempt horizontal fracturing with propping to achieve adequate permeability. Each hole will be cased to a depth of 2,300 feet and cored opposite the chimney interval. Pressure

and flow tests will be conducted in the same manner as with BR-5.

3. The three production wells, BR-5, BR-10A and BR-10B, will be equipped with 2⅞-inch tubing and liquid lift equipment.

4. The compressor system installed in Phase III will be modified to provide the necessary pressure in the fractured zone and to overcome the necessary pressure drop at a flow rate of about 12 MMSCFD. In order to provide a capability for recycle of a fraction of the off-gas, it will be necessary to provide a combination system both to pressurize the added air to the system pressure at the injection well heads and to offset the pressure drop of the recycle gas up to the production well-head. The 6,000 brake horsepower capability provided in Phase III should be adequate to provide the flow requirements indicated.

5. Two additional wells, BR-11A and BR-11B, will be drilled to a depth of 3,400 feet about 20 feet outside the wall of the chimney. These holes will be drilled and cased to a minimum ID of 6 inches to a depth of about 2,300 feet. A directional survey will be made of each hole after completion. During the course of the treatment of the fractured zone, these holes will be used for periodic wire-line temperature surveys through the depth of the producing section of the oil shale formation. Periodic gas samples may be taken from selected intervals of these wells. At the conclusion of the treatment of the fractured zone, these holes can be used to provide core samples through the treated section of the oil shale.

6. Provided that the treatment of the fractured zone with production from wells BR-10A and BR-10B shows satisfactory results, two additional production wells, BR-12A and BR-12B, will be located and drilled to the same specifications as BR-10A and BR-10B, except that they will be spotted about 80 feet outside the chimney wall. The exact distance will depend upon the results of previous fracture studies and oil shale treatment. Limited fracture studies will be made in drilling these wells. These production wells will use tubing and liquid lift equipment transferred from other wells.

7. Two additional wells, BR-13A and BR-13B, will be drilled to the same specifications as BR-11A and BR-11B except that they will be spotted about 60 feet outside the chimney wall. These wells will also be used for periodic temperature survey profiles as well as for recovery of gas samples during treatment of the sector beyond the first set of production wells. After completion of treatment of the sector, holes BR-13A and BR-13B can be used, to recover cores in the treated zone of the formation.

8. No additional aboveground storage requirements are envisaged for either oil or water during Phase IV.

9. During the treatment of the fracture zone, periodic temperature profiles will be taken through the wells provided for this purpose. At the surface, continuous measurements of the important process parameters will be made (ambient flow rates, temperature and pressure). Periodic or continuous sampling will be made of the composition of the gaseous effluent. Gas samples will be analyzed for chemical composition and radioactivity. Periodic measurement will be made of the volumes and densities of oil and water samples recovered. The radioactive contaminants of the liquid products will be continuously monitored. The composition of the saline constituents of the water fractions will be periodically determined.

10. At the conclusion of Phase IV and in the absence of any new experimental requirements, the aboveground process equipment will be disposed of and the surface of the land will be returned substantially to the same condition in which it was at the beginning of the experiment.

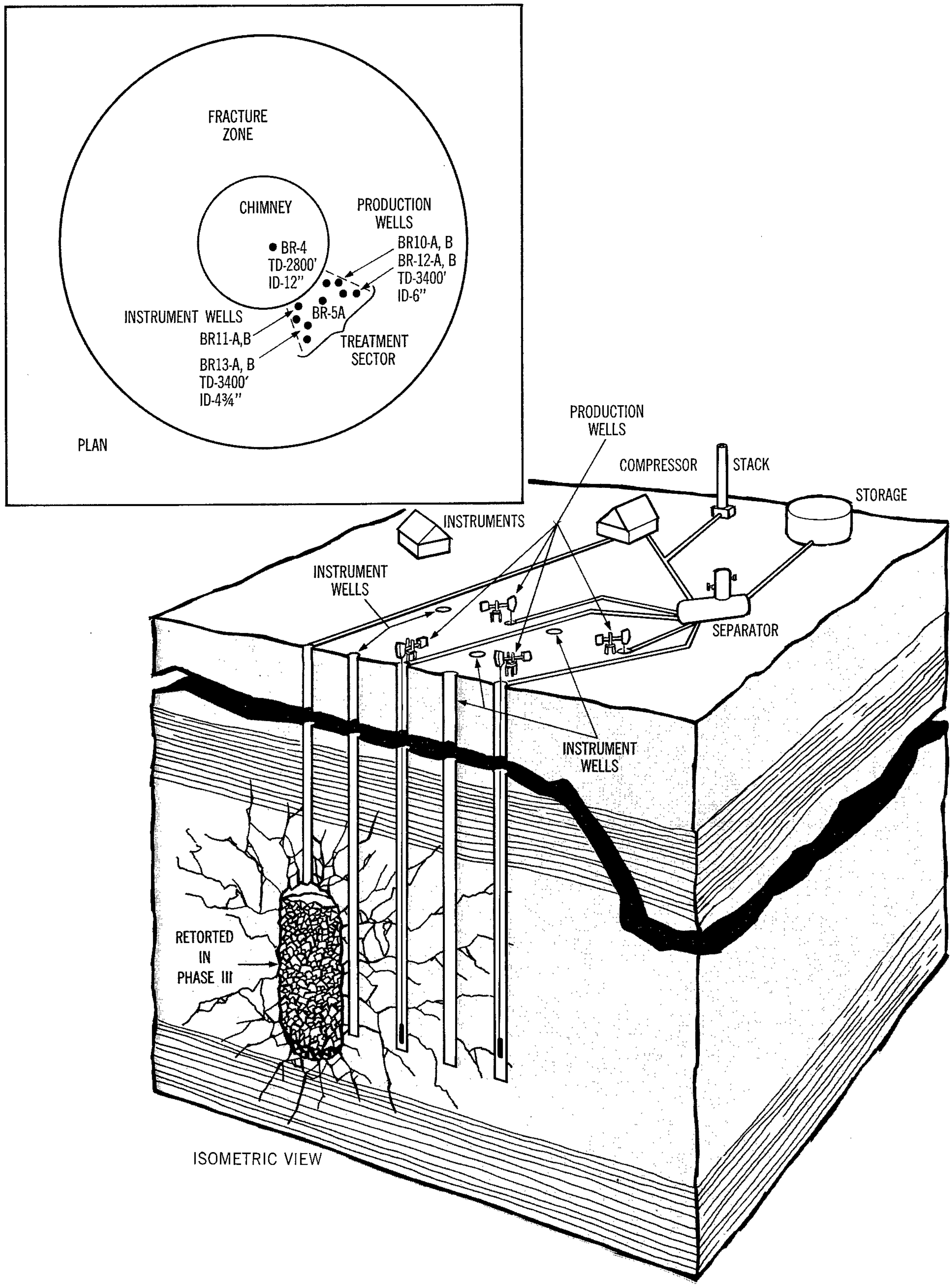


Figure 15. Phase IV Wells.

TABLE 7—WELL SPECIFICATIONS FOR PHASE IV

	BR-4	BR-5	BR-10A BR-10B
Purpose	Injection	Production	Production
Distance from GZ	25 feet	160 feet	160 feet
Total Depth	2800 feet	3400 feet	3400 feet
Minimum ID	12 inches	6 inches	6 inches
Drilling Fluid	mist	mist	mist
Casing Size and Depth	existing	existing	7⅝ inches to 2300 feet
Tubing	existing	from BR-6	from BR-7P and BR-9
Cement	to surface	to surface	to surface
Logs	none	none	γ-n Direction survey
Completion	existing	production tubing and liquid pump	production tubing and liquid pump

	BR-11A BR-11B	BR-12A BR-12B	BR-13A BR-13B
Purpose	Temperature Survey and Coring	Production	Temperature Survey and Coring
Distance from GZ	140 feet	200 feet	180 feet
Total Depth	3400 feet	3400 feet	3400 feet
Minimum ID	4¾ inches	6 inches	4¾ inches
Drilling Fluid	mist	mist	mist
Casing Size and Depth	5½ inches to 2300 feet	7⅝ inches to 2300 feet	5½ inches to 2300 feet
Tubing	2⅞ inches	2⅞ inches	2⅞ inches
Cement	to surface	to surface	to surface
Logs	γ-n direction survey	γ-n direction survey	γ-n direction survey
Completion	tubing for surveys	production tubing and liquid pump	tubing for surveys

SUPPLEMENTAL RESEARCH

Phase I and Phase II

EXPLOSIVE PERFORMANCE. A limited number of diagnostic measurements of the energy yield and other performance characteristics of the nuclear explosive will be required as a part of the Bronco experiment. These measurements will be conducted at shot time, with the exception of the analysis of melt samples recovered in post-shot drilling.

ROCK PROPERTIES. Samples of pre-shot core from the vicinity of the detonation point will be subjected to laboratory tests to determine their radioactivity, chemical composition, and the following physical properties:

1. Hydrostatic compressibility up to 40 kilobars.
2. Triaxial tests at various confining pressures.
3. Tensile strength.
4. Hugoniot elastic limit.
5. High-pressure Hugoniot equation of state.
6. Sonic velocity.

These data will be used as input for computer calculations of the shock wave, cavity growth, fracturing, and collapse leading to chimney formation. Core samples from post-shot holes will be analyzed for radioactivity and examined in the laboratory for permanent physical changes resulting from the explosion.

GAS SAMPLING. Samples of gas will be taken in several post-shot holes to determine the extent to which radioactivity has penetrated the formation. These samples will be taken with downhole bottles on a wire line or drawn to the surface from packed-off intervals through tubing. The gas will be analyzed for chemical composition and radioactive species. This information will be helpful in evaluating the fracturing caused by the explosion, leading towards eventually establishing the fracturing mechanism.

DYNAMIC EARTH MOTION. Holes BR-3 and BR-E will be fitted with peak pressure gauges, stress history transducers, and shock velocity instruments. Data from these instruments will be useful in checking the accuracy of computer code predictions of shock wave history and cavity growth.

GROUND SURFACE MOTION. Accelerometers and velocity gauges will be used to measure ground surface motion within a few miles of surface zero. These data will be used in establishing minimum safe distances for equipment and facilities for subsequent explosions in the same vicinity.

OTHER THEORETICAL WORK. Computer predictions will be made of the ground surface motion, the seismic wave, and the possible interaction of the chimney with overlaying aquifers. Computer computations related to recovery of oil from the chimney may also be made, in connection with Phase III.

Phase III and Phase IV

THERMODYNAMIC AND PHYSICAL PROPERTIES OF OIL SHALE. In situ retorting research studies at the Bureau of Mines Laramie Petroleum Research Center have been designed to provide information needed as a basis for the development of efficient methods for recovering shale oil from oil shale broken by underground nuclear explosions. Measurements have been made of the following thermodynamic properties: specific heat, heat requirements for retorting, thermal decomposition rates of oil-shale carbonates, thermal conductivity, and thermal diffusivity. Research has also been directed toward investigating the physical properties of oil shale, including the compressive strength of raw, retorted, and burned shales. The work is continuing.

LARAMIE 10-TON RETORT. A superior recovery technique must insure efficient heat utilization as well as the conversion of an optimum amount of the organic matter to a liquid product. The present 10-ton retort experiment is designed to investigate the retorting of ungraded oil shale under conditions similar to those expected in a nuclear chimney. Retorting studies to date have been made on mine run shale charges containing pieces as large as 20 inches in two dimensions. The third dimension has varied from several inches to 3 or 4 feet. Yields as high as 80 percent of Fischer Assay have been achieved.

CARBON RESIDUE STUDIES. Another current study will yield information on the maximum amount of heat obtainable by burning the carbonaceous residue remaining on spent shale. Results of this study should show whether a major portion of the heat required for retorting oil shale underground can be obtained by burning the organic residue remaining in the shale after retorting, or whether the heat should be generated by burning some of the product gas.

LARAMIE 150-TON RETORT. A new retorting experiment, larger than the present 10-ton operation is proposed. The retorting characteristics of ungraded shale

containing pieces as large as 4 feet in two dimensions will be determined. It is proposed that this experiment be conducted on shale charges of 100-150 tons, using a retorting vessel 12 feet in diameter and 45 feet high. Temperature and gas composition as functions of time and position in the bed will be recorded. Provision will be made for varying the air rate from 10,000 to 15,000 standard cubic feet per ton and the ratio of recycle gas to air from 0 to 1.5. Retorting rates will be varied but will probably average about 2 feet per day (5 $lb/hr/ft^2$ of retort cross section). It is proposed to operate the equipment at slightly elevated pressures.

From data taken in the course of retorting runs, and from careful examination of the contents of the retort at the conclusion of each run, some insight into the question of combustion front stability will be gained.

OIL SHALE CRUSHING STUDIES. The crushing tendencies of various grades of oil shale when subjected to retorting conditions such as might be encountered during the retorting of the rubble column of a nuclear chimney are currently being investigated. The equipment used for this work consists of an externally heated cylindrical vessel having a capacity of approximately 150 pounds of shale. Provision is made for compressing the bed by loading with a hydraulically-operated piston. Pressures of up to 500 psi, equivalent to a bed depth of approximately 1,000 feet, can be applied. Data will be indicative of the ability of various grades of shale to resist crushing and attendant reduction of bed permeability during retorting. Crushing studies will be made at subretorting temperatures as well as at retorting temperatures, and on retorted and burned shales as well as on raw shale.

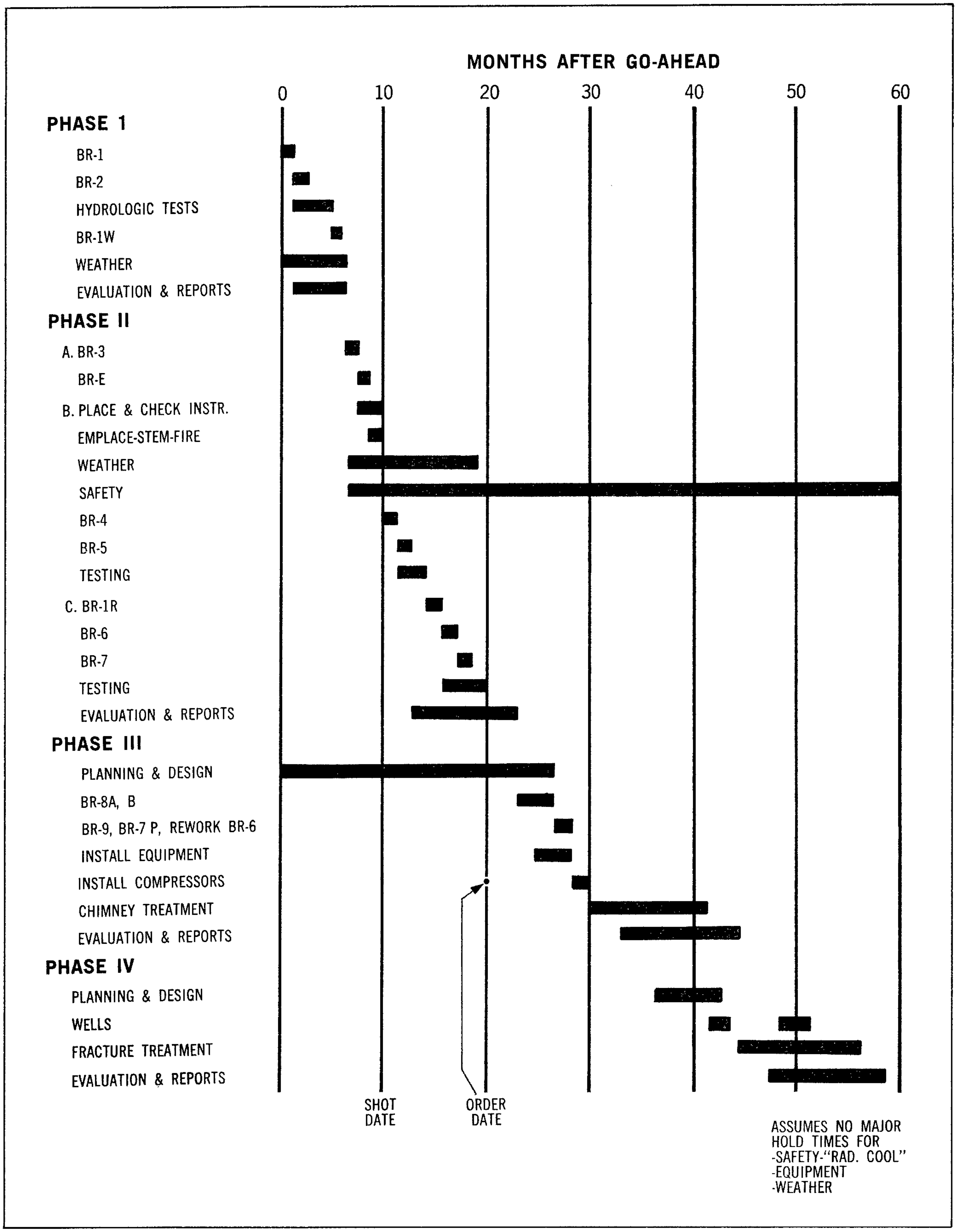


Figure 16. Estimated Project Bronco time schedule.

APPENDIX A*

DISTRIBUTION OF RADIONUCLIDES IN GROUND WATER IN THE PICEANCE CREEK BASIN

by: Frank W. Stead
U. S. Geological Survey

The radionuclides released from an underground nuclear explosion are initially distributed by direct explosive action in the immediate vicinity of the explosion. At some time, these nuclides may be transported by ground water to sufficient distances to raise problems of water management. Reviewed separately are: (1) the nature and amount of radionuclides produced by underground nuclear explosions, (2) the initial distribution of the biologically significant nuclides and (3) the possible transport of these nuclides by ground water. For purposes of this discussion it is assumed that a 50-kiloton part-fission part-fusion explosive will be used.

Activation Products

The exact amount of each activation product generated by the neutron flux from a nuclear explosion depends on the chemical composition of the rock. The activities induced in average crustal material are relatively short-lived.[32,33] At the end of one year, the induced activities, except for Co^{60}, are insignificant.

The composition of oil shale from a drill hole near the depositional center of the Piceance Creek Basin is given in Table 8. It is probable that the composition of the shale anywhere near the center of the Basin would be similar. In general, with increasing distance from the depositional center, the amounts of nahcolite and daw-

*Appendix A is a general review of the ground water system of the Piceance Creek Basin as it might be affected by an underground nuclear explosion, and was prepared at the request of the San Francisco Operations Office of the AEC. A study of the problems directly related to Bronco would be conducted by the Nevada Operations Office of the AEC when the technical concept and the shot location have been established.

TABLE 8—COMPOSITION OF OIL SHALE IN JUHAN CORE HOLE 4-1 [16]

		Weight Percent
Organic matter: Content of raw shale		18.0
Ultimate composition of organic fraction		
Carbon	80.5	
Hydrogen	10.3	
Nitrogen	2.4	
Sulfur	1.0	
Oxygen	5.8	
	100.0	
Mineral matter: Content of raw shale		82.0
Mineral constituents:		
Nahcolite $NaHCO_3$	11.1	
Dawsonite $NaAl(CO_3)(OH)_2$	9.5	
Quartz	25.0	
Dolomite	23.0	
Feldspar (K)	6.0	
(Na)	5.0	
Pyrite	1.5	
Water	1.5	
	100.±	

Based on analyses of 761-foot section, from 1,842 feet to 2,603 feet, in Juhan Core Hole 4-1, SW ¼, NE¼, Sec. 4. T. 2 S., R. 98 W., Rio Blanco Co., Colorado.

sonite would decrease, and would be replaced by increasing amounts of quartz and clay minerals.

Although the saline-rich zone in the Piceance Creek Basin contains a relatively high concentration of sodium, at 4 to 5 percent (by weight), it is not significantly greater than the average amount of sodium in the earth's crustal rocks at roughly 3 percent. The activation product, Na^{24}, with a 15-hour half-life, would not be present in significant amounts after the explosion and within a few months, it would be difficult to find a trace of Na^{24}.

The activation product, Fe^{59} with a 45-day half-life, would not be present in significant amounts as the Fe_2O_3 content of the oil shale is not more than about 3 percent, approximately the crustal abundance.

The activation product, Co^{60}, with a 5.2-year half-life, would be present in minor amounts, as oil shale probably contains 1 to 2 parts per million of cobalt. The total amount of Co^{60} from a nominal 50-kiloton nuclear explosion might be on the order of 100 curies.

The small amount of nitrogen in the oil shale, less than 0.5 percent, would lead to a trivial amount of C^{14}, insufficient to warrant consideration.

Fission and Fusion Products

At the end of one year Sr^{90} and Cs^{137}, both with about 30-year half-lives, are the principal remaining fission products of recognized biological importance. It is assumed that Sr^{90} is the more significant radionuclide, as Cs^{137} is more firmly held on the solid by exchange mechanisms than is Sr^{90}. The gaseous fission products, Xe^{133} and Kr^{85}, are not considered significant as potential contaminants in ground water. If one-half of a 50-kiloton explosion were fusion energy release, about 25×10^4 curies of tritium with a half life of 12.3 years would be produced.

Initial Distribution

The initial distribution in oil shale of 4×10^3 curies of Sr^{90} from the 25-kiloton fission energy release can be calculated on the basis of four conservative assumptions: (1) the radius of the cavity is 100 feet, (2) the radius of the fractured zone is 220 feet, (3) the density of the oil shale around the point of explosion is 2.2 (g/cc), and its porosity (water saturated) is 0.02 (2 percent), and (4) radionuclides are distributed only in the chimney by direct explosive action, and post-shot collapse of the chimney into the cavity will not affect the nuclide distribution.

On these assumptions, the mass of solids in the chimney will be 2.38×10^{12} grams, the mass of water in the pore space will be 2.2×10^{10} g. (or ml), and the total mass will be 2.4×10^{12} g.

Assuming that Sr^{90} is all soluble and uniformly distributed throughout the oil shale in the chimney, its initial concentration in the total mass would be 4.0×10^3 curies in 2.4×10^{12} g, or 1.7×10^{-9} c/g.

When equilibrium is reached in the exchange of Sr^{90} between the oil shale matrix and the contained pore water, the amount of Sr^{90} in the water is expressed by the equation:

$$K_d = \frac{\text{Activity-solid}}{\text{Activity-water}} \times \frac{\text{Volume-water}}{\text{Weight-solid}}$$

where K_d, the distribution coefficient for Sr^{90} in oil shale, is estimated at about 100. The Sr^{90} activity in the water is then 0.37 curies; and the Sr^{90} concentration in the water, 0.37 curies in 2.2×10^{10} ml, is then 1.7×10^{-11} c/ml.

The only long-lived activity of possible importance induced in oil shale would be Co^{60} (5.2-year half-life) at no more than 100 curies. Thus, 100 curies would be distributed throughout the crushed zone, and its initial concentration would be 4.5×10^{-11} c/g. Co^{60} is analogous to Sr^{90} in exchange behavior, and after reaching exchange equilibrium between oil shale and the pore water, its concentration would be 4.5×10^{-13} c/ml.

The fusion reaction in the explosion would produce 25×10^4 curies of tritium (H^3), the preponderance of which would be in the form of tritiated water. The H^3 concentration in the pore water would be 25×10^4 curies H^3 in 2×10^{10} ml, or 1.25×10^{-5} c/ml. It is assumed conservatively that this tritium concentration will be reduced by radioactive decay and by dilution with ground water outside the chimney, but not by exchange mechanisms.

Transport of Radionuclides

Evaluation of the transport of radionuclides by groundwater solutions requires: (1) determination of the velocity and direction of regional ground water flow, (2) determination of chemical composition of the ground water and of the physical and chemical properties of the rock matrix, and (3) determination of the specific K_d's for specific radionuclides, using representative samples of the rock and the contained ground water.

For the Piceance Creek Basin, the velocity and direction of flow are not well known. A reasonable assumption is that the flow rate is from 10 to 100 feet per year, radially inward from the structural rim and then northward via Yellow and Piceance Creeks drainage. Chemi-

cal analyses of representative ground water from the oil shale indicate a high sodium bicarbonate type with minor amounts of Ca, Mg, and K.[34]

The distribution coefficient, K_d, is defined as the ratio of the concentration of a particular radionuclide on the solid to the concentration of that nuclide in the adjacent solution, at equilibrium. As ground-water solutions move away from the saline-rich and oil-rich zone in the center of the basin, where presumably the nuclear explosion will occur, the clay mineral content will markedly increase with corresponding decrease in the carbonate minerals. It follows that the K_d for Sr^{90}, estimated to be about 100 if the point of explosion is in the high saline zone, will tend to become larger, probably in the range of 500 as the clay minerals become abundant.

For the proposed 50-kiloton explosion in the oil shale the transport of the radionuclides Sr^{90} and H^3 can be calculated to a first approximation, assuming that: (1) the ground-water flow rate is 100 feet per year, (2) the value of K_d is 500, and (3) the flow is completely laminar. The average flow rate of a single nuclide such as Sr^{90} is related to the flow rate of the ground water by the equation[35]

$$\text{Flow (ion)} = \frac{\text{Flow (water)}}{1 + K_d \rho}$$

where K_d is the distribution coefficient for that ion, and ρ is the ratio of the mass of the solid to the volume of the water per unit volume of the rock. Using a K_d of 500, the flow rate for Sr^{90} is retarded by ion exchange between the solid and the water to 1/50,000 of the flow rate of the ground water. Should H^3 be present, however, it would not enter appreciably into ion exchange reactions, although as tritiated water it might exchange with chemically bound water in the rock matrix, and thereby be slightly retarded in respect to the ground-water flow rate, by a few percent in clean sands to possibly 50% in a rock high in clay minerals.

It is reasonable to assume that the travel path of ground water from around the point of explosion to where it contributes to surface water flow would be on the order of several miles – for convenience, assume 5 miles or 25,000 feet. At a ground-water flow rate of 100 feet per year, travel time to the outlet would be roughly 250 years. For Sr^{90} in the ground water, an additional retardation factor of 50,000 must be used; obviously by the end of this time period, the Sr^{90} would have completely decayed. For H^3, with a 12.3-year half-life, the 250-year period would lead to a decay to 1×10^{-6} of the original activity, or a reduction of six orders of magnitude.

Conclusions

1. On the basis of the available data and assumptions made, no contamination of surface water sources seems probable.

2. Should it become necessary to remove water from a rubble-filled chimney, a water disposal problem may arise, due to the Sr^{90} and H^3 content in the initial water flow from the chimney. Therefore, it is recommended that the area surrounding ground zero be dewatered prior to detonation.

APPENDIX B

POTENTIAL RADIOACTIVE CONTAMINANTS IN OIL PRODUCED FROM NUCLEAR-BROKEN OIL SHALE

by: C. A. Blake and D. J. Crouse
Oak Ridge National Laboratory

It is known from experience with many underground nuclear tests that most of the fission products and induced radionuclides produced during the nuclear blast will be trapped in the fused rock (puddle glass) that accumulates at the bottom of the chimney. The crushed shale, however, will be contaminated with fusion produced tritium, presumably mostly as tritiated water and certain fission products, for example Sr^{90} and Cs^{137}, which have gaseous precursors, and Ru^{106} which forms volatile compounds. The quantity of these radionuclides which may appear in the product oil and in the gases which are produced during the retorting are important to the future of nuclear explosives for crushing shale. This appendix presents the initial results of laboratory tests which are currently being carried out by ORNL to give an indication of the fate of the radionuclides during shale retorting. However, without an actual nuclear test it is impossible to assess in detail the potential problems of industrial safety involved in producing and handling the oil.

QUANTITIES OF RADIONUCLIDES PRESENT. The amounts of the individual fission products and tritium produced by a detonation of a given yield depend on the type of explosive used. This evaluation assumes that most of the energy would be derived from fusion. If retorting starts about 15 months after the shot, the tritium activity will be more than 95% of the total activities present. In addition, a small amount of radioactive material formed by neutron activation of the shale surrounding the explosives would be present. Irradiation of a sample of Green River oil shale in the Oak Ridge Research Reactor indicated that Sc^{46}, Fe^{59}, Mn^{54}, and Zn^{65} would probably be the most important of the long-lived induced radionuclides. As indicated above it is anticipated that most of the tritium (as water) and significant quantities of Ru^{106}, Cs^{137}, Sr^{90}, and Y^{91} will be present in the shale rubble. The gas within the void volume will contain tritiated water vapor (a small fraction of the total tritiated water), tritium gas and Kr^{85}. Most of the remaining fission and activation products should be trapped in the puddle glass.

CONTAMINATION OF THE RETORT-OFF-GASES. The gases initially emerging from the retort during retorting will include krypton, but more significantly, tritium, assumed to be mostly as tritiated water vapor. It is estimated that a 50 kt shot would produce large quantities of tritium and, because its half-life is 12.3 years, this amount would nearly all be present when retorting starts. The concentration of radionuclides in the gases and consequently the handling of the gases depends on a number of factors. For example, essentially all of the krypton and that portion of the tritium present as tritium gas should be flushed readily from the chimney. The rate at which the tritiated water will be removed will depend upon the extent of its diffusion into the shale and subsequent equilibration with the water bound in the shale. It is possible that a significant portion of the tritiated water will remain at the shale surface in a form which can be evaporated and can thus be removed by passing a relatively few void volumes of hot gas through the chimney. Tritiated water bound in the shale, however, will be released slowly; initial laboratory tests indicate that, in retorting, the bound water is released at a temperature only slightly lower than that of the oil. In addition, the tritium concentration in the gas stream will be affected by the ratio of the volume of gas recycled to the retort to the volume discarded.

In any case, in designing the facility, careful consideration must be given to providing for dilution of the off-gases to an acceptable level prior to discard or for dispersing them to the atmosphere in a manner which will ensure adequate dilution prior to contact with on-site personnel or with the off-site population.

CONTAMINATION OF THE OIL. Conceivably, the product shale oil could be contaminated with radionuclides at several points in the process, for example:

1. Exchange of tritium and hydrogen between water and the shale oil during the retorting phase.
2. Dissolution of oil-soluble fission product compounds present in the shale rubble and puddle glass.

3. Inclusion of tritiated hydrocarbons which may be produced in the fireball and which will be dispersed in the chimney.

Initial tests in a small laboratory retort showed that, when shale was wetted with tritiated water prior to retorting, the product oil contained tritium compounds which were not removed by washing the oil with water. The shale had been moistened with 4.5 curies of H^3/ton. The washed oil contained about 1 millicurie H^3/gallon of oil which was about 0.5% of the tritium originally added to the system.

In other laboratory tests, when shale oil was heated (200°C, 4 hr) with radioactive debris in the forms of rubble and puddle glass from an underground test shot, small amounts of radionuclides (predominantly Ru^{106}) were detected in the oil. The fraction removed from the puddle glass was much lower than from the rubble.

It must be emphasized that such a large extrapolation must be made from the conditions of these tests to those holding in the nuclear test that these fragmentary data should be used only to support the contention that contamination of the oil may occur.

Additional laboratory tests simulating the retorting operation are being made to provide a better basis for predicting the behavior of the various radionuclides in the processing cycle and the type and degree of contamination of the oil that may result. The study will also include consideration of methods for minimizing contamination of the oil and methods for decontaminating the oil both at the site and in subsequent refining operations.

APPENDIX C

GEOLOGY AND HYDROLOGY OF PICEANCE CREEK BASIN

by: Frank W. Stead, John R. Ege, and Frank A. Welder
U. S. Geological Survey

Geology

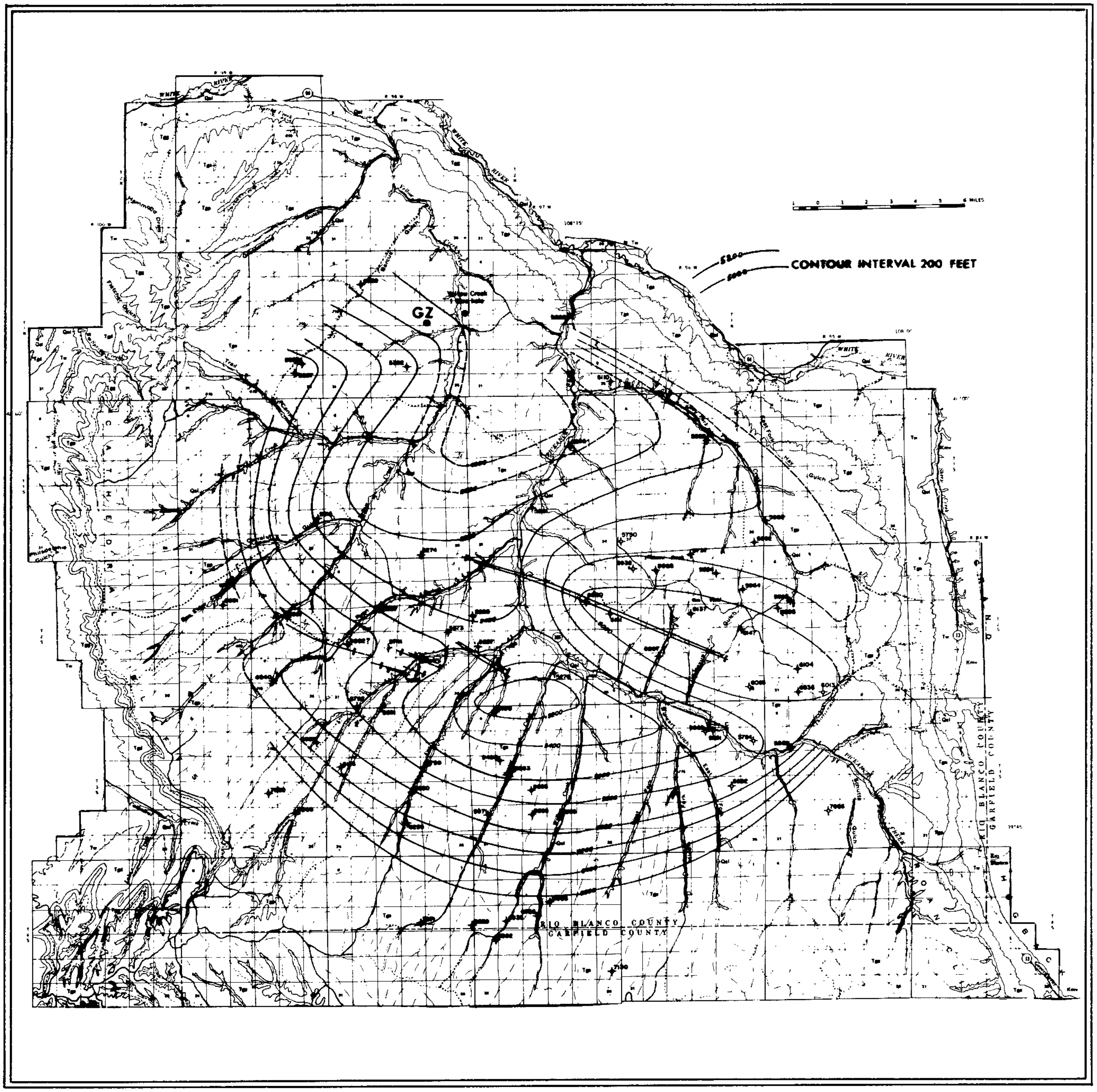
The lacustrine Green River Formation in the Piceance Creek Basin is as much as 3,000 feet thick, and is divided into five members. Starting at the base these are the Douglas Creek, Garden Gulch, Anvil Points, Parachute Creek, and Evacuation Creek Members.[36] The Parachute Creek Member consists of kerogeneous marlstone and contains the rich oil shale and associated dawsonite and nahcolite deposits. The Member ranges in thickness from about 850 feet on the margins of the Piceance Creek Basin to a maximum of about 1,800 feet. Dawsonite, nahcolite, halite, and other sodium minerals are commingled with oil shale and form a saline-rich zone in the lower half of the Member. Near the depositional center of the Basin the saline-rich zone attains a thickness of at least 900 feet. The top of the saline-rich zone is a dissolution surface. Above is a leached zone of broken and brecciated oil shale, several hundred feet thick, from which water-soluble minerals have been removed by ground water. This zone is water bearing and active removal of water-soluble minerals may still be taking place.

Overlaying the Parachute Creek is the Evacuation Creek Member, which consists chiefly of sandstone, shale, siltstone, and barren marlstone. It is the uppermost Member of the Green River Formation and is exposed over most of the Piceance Creek Basin. A thickness of 1,250 feet is the greatest known thickness in the Basin.

The major structural elements within the Piceance Creek Basin involving the Green River Formation reflected on the base of the mahagany zone (black marker) are two small, generally northwest trending, synclines and the Piceance Creek dome (Figure 17). The dome is a gas-producing structure. Several northwest-trending faults, commonly paired as grabens and of small displacement, cut the Piceance Creek dome and an eastward-plunging anticlinal nose just west of the dome. Thickening of the Parachute Creek Member coincides with the synclines suggesting pre-Parachute Creek folding. Tectonics further modified the intrabasin structure in post-Parachute Creek time forming the Piceance Creek dome.

Oil Shale Deposits

The Parachute Creek Member in outcrop is subdivided into upper, middle and lower oil shale zones with barren or oil-poor units separating the three oil shale zones.[36] However, in the subsurface toward the deepest parts of the Basin, the lower of the two barren units becomes oil bearing and the lower and middle oil shale zones coalesce (Figure 18).[37] It is this coalesced middle-lower oil shale zone that is pertinent to the in situ oil shale feasibility study.



CONTOURS ON THE BLACK MARKER, PARACHUTE CREEK MEMBER OF THE GREEN RIVER FORMATION

Figure 17. Geologic structure map of Northern Piceance Creek Basin.

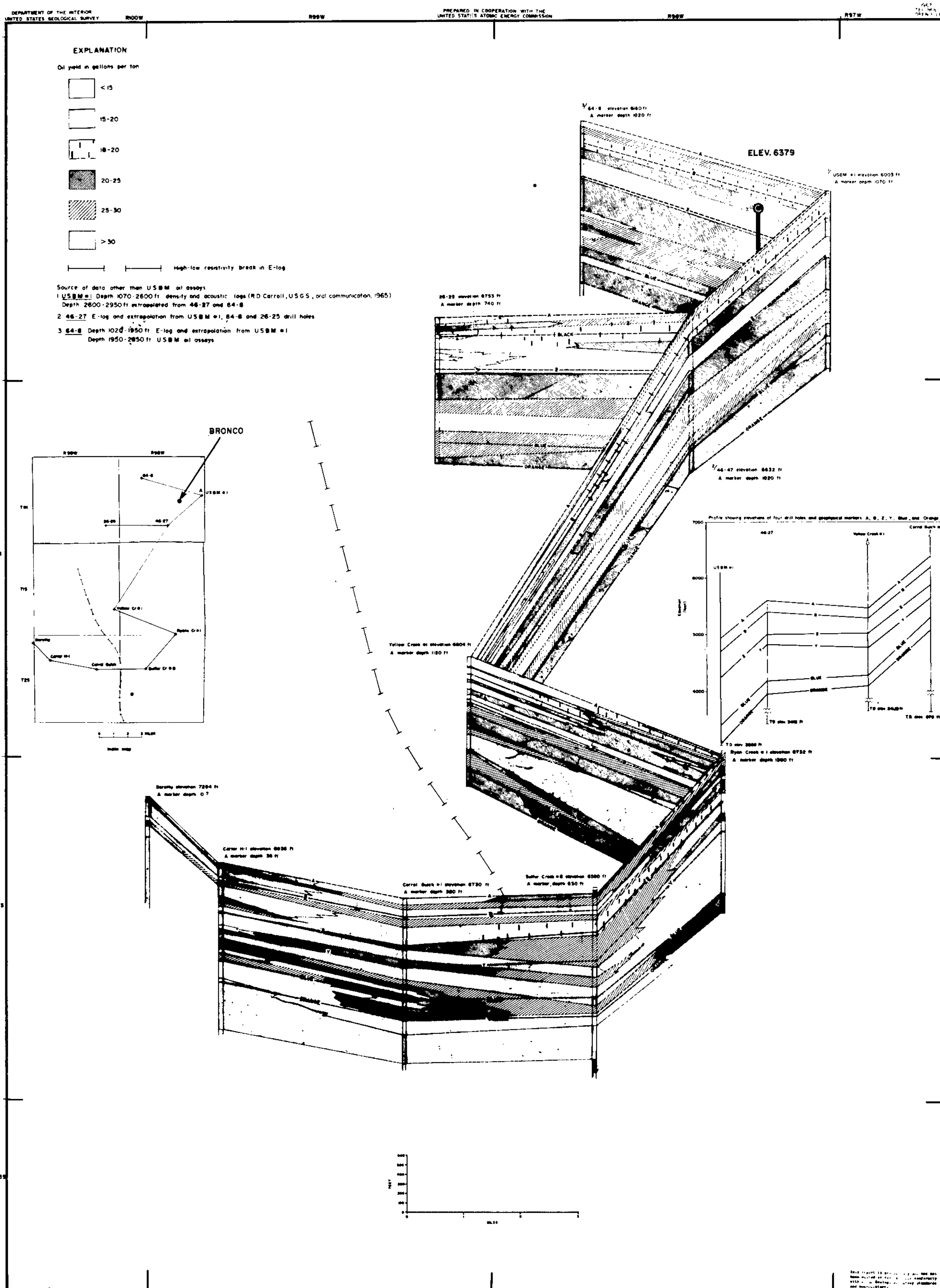


Figure 18. Geologic fence diagram showing stratigraphic features.

Arbitrarily defining "rich oil shale section" as oil shale yielding not less than 20 gallons of shale oil per ton of rock, it is possible to divide the Piceance Creek deposits into rich and lean oil shale sections. Figure 19 is an isopach map estimating the thickness and extent of the rich oil shale section in the western half of the Piceance Creek Basin. The isopach lines indicate that oil shale, yielding more than 20 gallons of shale oil per ton and having a minimum thickness of 1,000 feet, exists in an area covered by T. 1 S., T. 1 N., and R. 98 W.[37]

Figure 20 is an isopach map showing the thickness of overburden between the top of the rich oil shale section and a plane at the ground surface representing the stream gradient. The isopach lines indicate that a minimum overburden thickness of 1,200 feet exists in an area covered by two townships. This region coincides with the greater than 20 gallons oil shale section having a minimum thickness of 1,000 feet.

Of special interest to in situ retorting is a leached zone, that occurs in the center of the Basin. This zone is the interval where the nahcolite and other salts have been dissolved out by ground water. The dissolution results in a volume loss in the leached interval and subsequent collapse of the shale. The leached interval can be recognized in the core by a high degree of core loss, broken core and barren nahcolite vugs. In USBM/AEC Colorado Core Hole No. 1 the zone of poor recovery lies between 1,595-1,745 feet. Below the zone of poor recovery the core is tight and competent and seems to be relatively impermeable.

In summary, available geologic information indicates:

1. A minimum 1,000-foot thick oil shale section that yields more than 20 gallons of shale oil per ton of rock exists in an area covered by T. 1 S., T. 1 N., and R. 98 W.
2. A minimum of 1,200 feet of overburden above the oil shale section exists in the same area.
3. USBM/AEC Colorado Core Hole No. 1 in Sec. 13 T. 1 N., R. 98 W. shows the zone of poor recovery, or leached zone, lies between depths of 1,595-1,745 feet and that below 1,745 feet to a depth of 3,140 feet (T.D.) the rock is tight and competent.
4. It is assumed that geologic conditions will be similar to USBM/AEC Colorado Core Hole No. 1 in an area enclosed by a circle of 2-miles radius.

Dawsonite and Nahcolite Deposits[16, 38]

Considerable interest is being expressed by industry in the economic possibilities of extracting alumina and soda ash from the dawsonite and nahcolite contained in the Green River oil shale. Dawsonite contains 35 weight-percent alumina, and nahcolite contains 65 weight-percent soda ash. It must be emphasized that dawsonite and nahcolite are present in rocks that already have great potential value for their shale oil content.

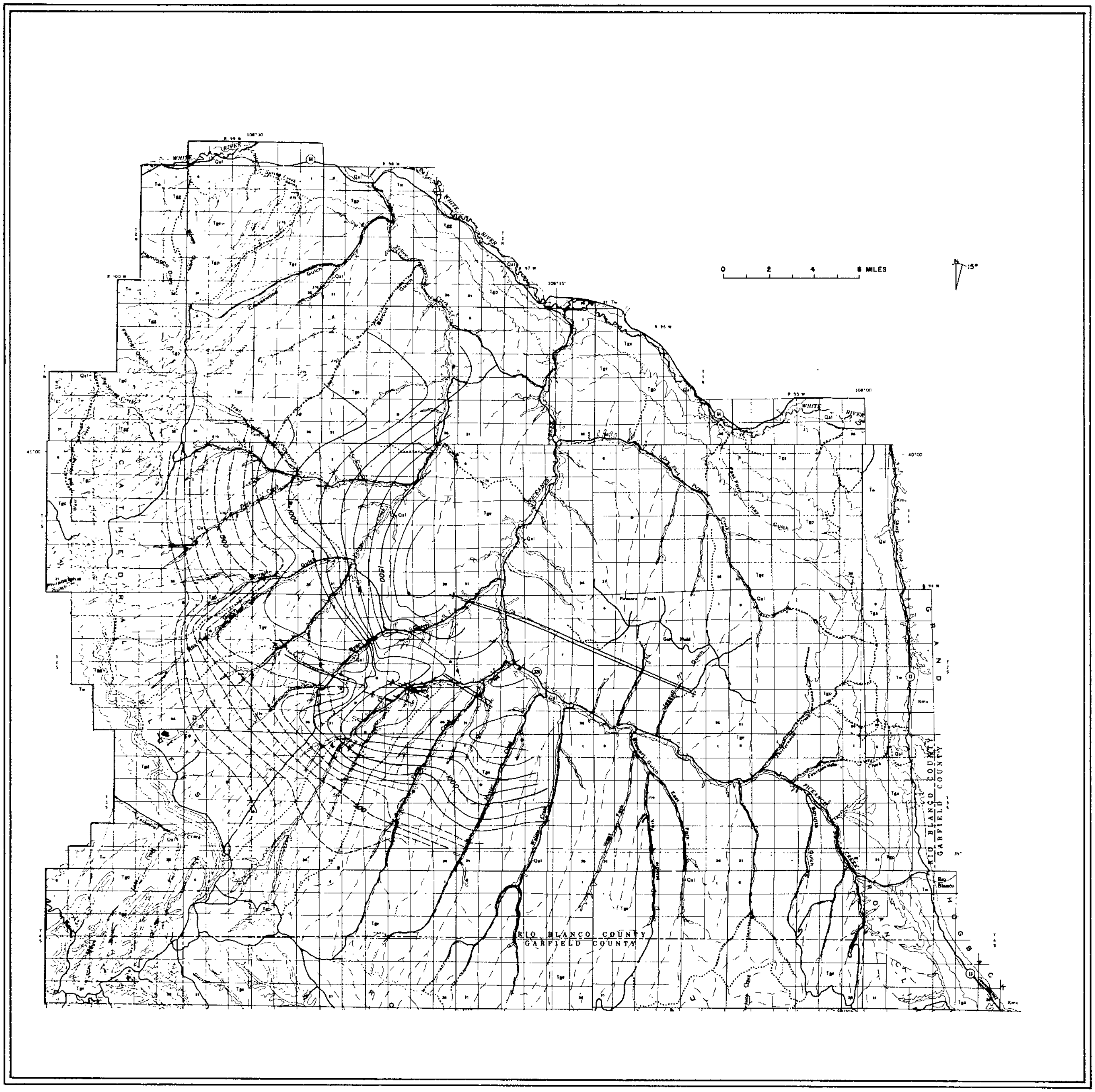
Dawsonite shows wide vertical and areal distribution in the northern part of the Basin. The thickness of oil shale continuously mineralized by dawsonite ranges from zero just south of the Rio Blanco County line to as much as 760 feet toward the center of the Basin.[38] In the Juhan Core Hole 4-1, located in the SW ¼ NE ¼ Sec. 4, T. 2 S., R. 98 W., dawsonite is distributed through a continuous zone at least 628 feet thick and averages 11 weight percent. Dawsonite is present discontinuously through several hundred feet of oil shale cropping out along the north side of the Basin. Near the center of the Basin the top of the dawsonite zone ranges in depth from 900 to as much as 1,900 feet below the surface.

Dawsonite occurs as microscopic crystals finely disseminated through the oil shale, as thin laminae along bedding planes, and in fissures and also in small vugs. The mineral is also found in some of the halite and nahcolite units. Because dawsonite is extremely fine grained, X-ray diffraction analysis is necessary for rapid, positive identification. Dawsonite, quartz, albite, potash feldspar, dolomite, and a few percent pyrite form the major fine-grained crystalline mineral constituents of the oil shale in the saline-rich zone. Clay minerals are conspicuously absent through most of the saline-rich zone.

Nahcolite is more abundant and widespread than dawsonite in the Piceance Creek Basin. Like dawsonite, nahcolite increases toward the depositional center of the Basin. Nahcolite units ranging in thickness from about 1 to 9 feet can be traced in the subsurface over an area of about 180 square miles. Disseminated forms of nahcolite have even greater distribution, but present data are too sparse to show its extent with any degree of accuracy.

Nahcolite occurs in both nonbedded and bedded forms in oil shale. Scattered through much of the saline-rich zone of the Parachute Creek Member are aggregates of coarse-bladed crystals of brown nahcolite. The aggregates range from a few inches to a few feet in diameter. Bedded forms of nahcolite include finely crystalline layers and units of honeycomb-like intergrowths of nahcolite and oil shale.

The amount of each potential resource in the Juhan core hole can be calculated on the basis of 1 square mile from the thicknesses and grades. The shale oil amounts to nearly 1 billion barrels. About 130 million tons of nah-



CONTINUOUS OIL SHALE SECTION YIELDING MORE THAN 20 GALLONS PER TON

Figure 19. Isopach map of oil shale thickness, Northern Piceance Creek Basin.

colite are present, or calculated as soda ash about 82 million tons. About 42 million tons of dawsonite alumina are present in 1 square mile. The total known bauxite reserves of the United States contain about 30 million tons of alumina. Thus, just 1 square mile in the Piceance Creek Basin contains about 1.5 times as much alumina as in the total bauxite reserves of the United States.

Hydrologic Setting Piceance Creek Basin

In the Piceance Creek Basin, the main source of groundwater recharge is precipitation, which averages from 12 to 26 inches per year, depending on altitude. Water enters the Green River Formation, moves downdip toward the center of the structural basin, leaves the bedrock, probably by way of fractures, enters the alluvium along stream valley, and finally leaves the basin by way of stream valleys. The principal aquifers are the alluvium along stream valleys and the Evacuation Creek and Parachute Creek Members of the Green River Formation. Runoff in Parachute, Piceance, and Yellow Creeks totalled 21,700 acre-feet for the water year ending September 30, 1965.

Little is known of the regional water-bearing capacity of the Green River Formation at depths to 3,000 feet below the ground surface. The information presently available is derived from hydrologic tests conducted in USBM/AEC Colorado Core Holes No. 1 and No. 2 located in the Piceance Creek Basin.

USBM/AEC Colorado Core Hole No. 1[30]

Pumping tests were conducted under open-hole conditions from the bottom of the casing at 750 feet to the total depth of 3,140 feet. The Evacuation Creek Member of the Green River Formation is present to a depth of 985 feet, and lies above the Parachute Creek Member. Pumping was at the rate of 113 gpm for 275 minutes, resulting in a drawdown of water level of 80 feet. The specific gravity is calculated at 1.7 gpm per ft. (gallons per minute per foot). In general, specific capacity decreases with time. Computed transmissibility for the interval between 750-3,140 feet is 3,900 gpd per ft. This figure cannot be considered accurate, but is probably of the correct order of magnitude. The water contained more than 17,000 ppm of dissolved solids, mostly sodium bicarbonate.

A deep-well current meter survey while pumping at the rate of 113 gpm with a drawdown of 80 feet indicated that most of the water came from between depths of 1,200 and 1,650 feet in the leached zone in the Parachute Creek Member, and that water was not entering the hole below a depth of 1,650 feet. These data suggest that the Parachute Creek Member below the base of the leached zone, at about 1,745 feet, is relatively impermeable and tight, and would not yield much water to a drill hole or to an explosion-produced chimney. In a later pump test, a packer was set at 1,800 feet, and the hole was pumped for 3½ hours below the packer. Due to interference from drilling mud in the hole, and in the formation, the test was inconclusive; however, it did indicate a minimum specific capacity of 0.04 gpm per foot, and a transmissibility of 20 gpd per foot. The maximum rate of flow during the test was 22 gpm.

USBM/AEC Colorado Core Hole No. 2[34]

USBM/AEC Colorado Core Hole 2 yielded 260 gpm while the Evacuation Creek Member was being cored with air as the circulating medium; specific conductance of the water was 1,100 micromhos per centimeter. The yield increased to about 500 gpm as coring progressed in the Parachute Creek Member to a total depth of 2,214 feet.

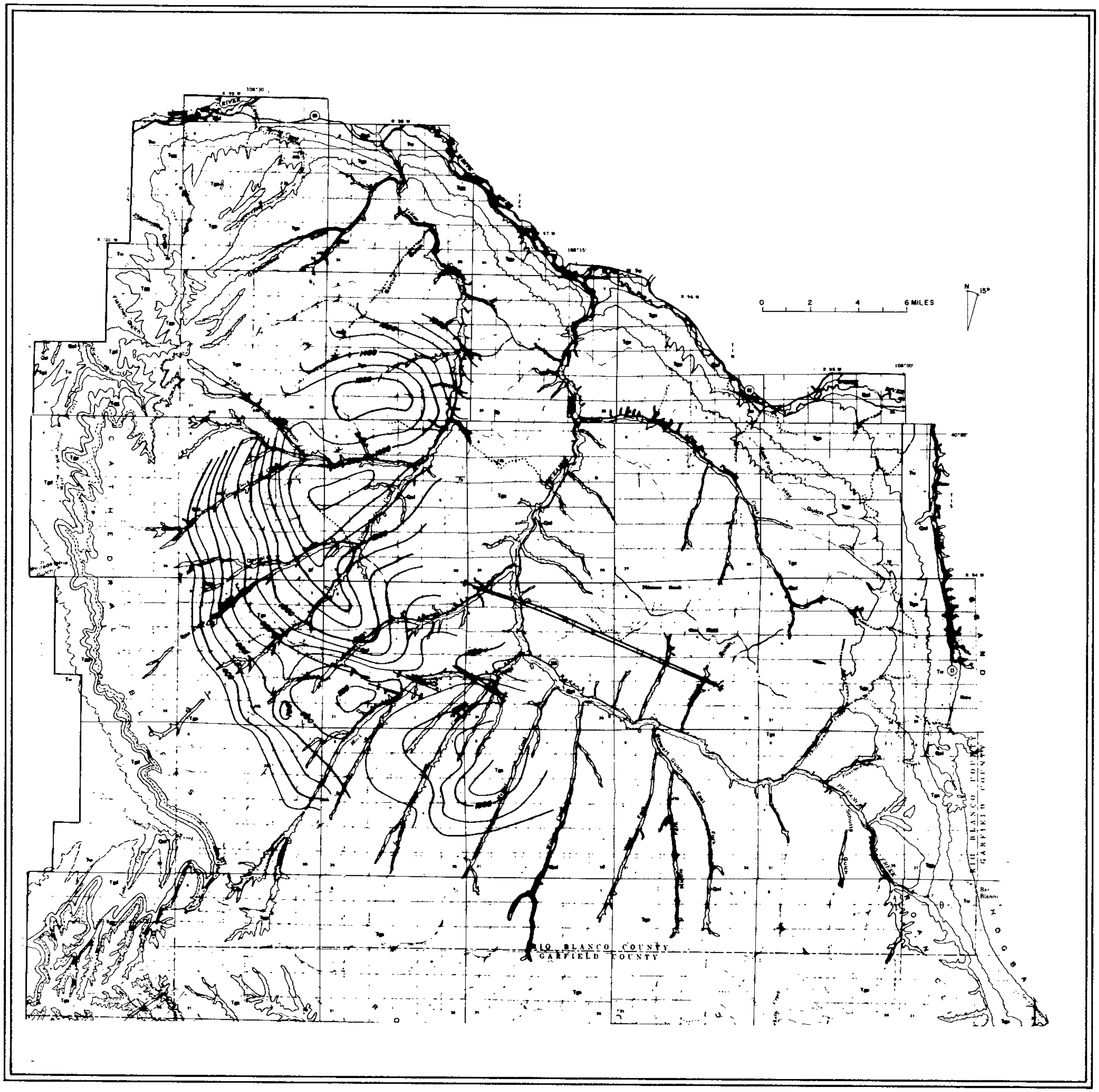
Pumping tests indicated a coefficient of transmissibility for the Green River Formation of about 3,500 gpd per ft. and a specific capacity of 3.6 gpm per ft. of drawdown after pumping an average of 93.4 gpm for 250 minutes from the open hole in the interval between 411 feet to 2,214 feet.

A packer was set at 1,500 feet in the Parachute Creek Member, below the leached zone, and an average of 74 gpm was pumped for 300 minutes. Although the water level in the zone below the packer had not stabilized before pumping began, and pumping was not continued long enough for the data to be analyzed by the modified nonequilibrium formula, the data indicate that the coefficient of transmissibility of the zone between 1,500 and 2,100 feet is probably less than 150 gpd per ft.

A deep-well current meter survey showed that about 30 gpm was entering the hole between depths of 1,200 and 1,400 feet, moving downward and leaving the hole between depths of 1,900 and 2,070 feet. All water movement was within the Parachute Creek Member. Analyses of water samples from the Parachute Creek Member show that the water is a sodium bicarbonate type having a specific conductance ranging from 900 to 2,200 micromhos per centimeter.

Test Data From Other Wells

The results of open-hole pumping tests of other wells tapping the Parachute Creek Member are shown in Table 9.



THICKNESS OF OVERBURDEN TO TOP OF THE CONTINUOUS GREATER-THAN-20 GALLONS PER TON OIL SHALE

Figure 20. Isopach map of overburden thickness, Piceance Creek Basin.

TABLE 9—HYDROLOGIC DATA FROM PICEANCE CREEK WELLS

Well	Location	Coefficient of Transmissibility (gpd per ft)	Specific Conductance (micromhos per cm)
American Petrofina 1 Gov't 10	Sec. 10, T. 1 S., R. 96 W.	2,000	969
Equity Oil Company 3 Oldland	Sec. 10, T. 3 S., R. 96 W.	2,000	2,400
Equity Oil Company 2 Oldland	Sec. 11, T. 3 S., R. 96 W.	1,100	2,500

Drawdown measurements made in Equity Oil 3 Oldland during the pumping of Equity Oil 2 Oldland, indicate a coefficient of storage of 1×10^{-5}.

Summary

Results of hydrologic study in the northern Piceance Creek Basin offer the following conclusions:

1. Groundwater supply for industrial or municipal purposes is limited to small withdrawals from the stream valley alluvium which is not very extensive, and from the bedrock which has low storage capacity (coefficient of storage). It is doubtful that more than a few thousand acre-feet of ground water per year could be withdrawn without causing widespread water-level declines, accompanied by encroachment of saline water into the fresh-water zones. Prospective water wells should be widely spaced.
2. The specific capacity of 1.7 gpm per ft. determined in Core Hole No. 1 under open-hole conditions may be representative of the upper 1,650 feet of the hole, as the current meter survey indicated no contribution below 1,650 feet.
3. Additional tests now planned in Core Hole No. 1 below 1,800 feet, that is, below the base of the leached zone, should provide information on the specific capacity and transmissibility of the lower part of the Parachute Creek Member. It is anticipated that the specific capacity and transmissibility in the interval below 1,800 feet will be much lower than in the upper part of the hole.
4. The groundwater conditions that may exist a few miles to the west of Core Hole No. 1, for example, in Sec. 15, T. 1 N., R. 99 W., should be closely similar to the conditions found in Core Hole No. 1.

TABLE 10—OIL YIELDS REPORTED FOR USBM/AEC COLORADO CORE HOLE NO. 1, PICEANCE CREEK BASIN[1]

Location: NE ¼, SE ¼, Sec. 13, T. 1 N., R. 98 W., Rio Blanco County, Colorado.

Collar Elevation: 6,003 feet *Total Depth:* 3,140 feet

Hole Depth[2] (feet)	Thickness (feet)	Elevation (feet)	Oil Yield[3]— Fischer Assay (gallons per ton)
986-1,100	114	5,017-4,903	10-15
1,100-1,184	84	4,903-4,819	25-30
1,184-1,354	170	4,819-4,649	15-20
1,354-1,554	200	4,649-4,449	20-25
1,554-1,770	216	4,449-4,233	10-15
1,770-1,996	226	4,233-4,007	20-25
1,996-2,100	104	4,007-3,903	15-20
2,100-2,210	110	3,903-3,793	20-25
2,210-2,340	130	3,793-3,663	30-35
2,340-2,738	398	3,663-3,265	20-25
2,738-2,820	82	3,265-3,183	15-20
2,820-2,900	80	3,183-3,103	10-15
2,900-3,133	233	3,103-2,870	0-5

[1] Fischer oil assays made in the U. S. Bureau of Mines' laboratory, Laramie, Wyoming.

[2] Intervals based on breaks in geophysical logs. [3] Reported in 5-gallon increments.

APPENDIX D

PRELIMINARY SAFETY EVALUATION FOR PROJECT BRONCO

by: R. L. Kinnamon, D. W. Hendricks, and R. A. Johnson, Nevada Operations Office, *U. S. Atomic Energy Commission*

Introduction

The AEC's Nevada Operations Office (NVOO) is responsible for the conduct of all AEC nuclear detonations. The NVOO will designate a Project Manager who will direct execution of the approved field program in conformity with established safety criteria. The Project Manager will assume responsibility for on- and off-site safety of personnel and property as directly related to the execution of the nuclear test event.

This appendix sets forth the preliminary safety evaluation for the Bronco experiment proposed for execution at a site near Core Hole No. 1, an exploratory core hole drilled by U. S. Bureau of Mines/AEC, to gather specific information on the shales of the Piceance Creek Basin in western Colorado. The experiment envisions use of a nominal 50 kt nuclear explosive emplaced at a depth of about 3,350 feet. Pre-shot drilling and logging would characterize the shot medium and determine the hydrologic acceptability both for technical and safety considerations. Measurements accompanying the shot would be made primarily to document the resulting effects and provide assurance that adequate measures had been taken to protect the population and participating project personnel, as well as to assure that damage potential in the off-site areas had been minimized.

Seismic

Underground nuclear explosions generate strong seismic pulses which impart severe ground motions at areas near the explosion. The amount of seismic energy that arrives at any location is dependent largely on the energy source or yield, the geologic medium through which the energy must travel, and the distance from the source. The earth's crust is an excellent attenuator of high frequency earth motions, and within a few thousand meters, these motions are greatly reduced. The low frequency motions are attenuated less rapidly and hence may be felt at much greater distance. Any seismic motion can be characterized by measuring with instruments which record the motions in terms of particle displacement, particle velocity and particle acceleration.

GROUND MOTION PREDICTIONS

The ground motion predictions are based on the detonation of a 50 kt nuclear explosive in a hard rock media. Figures 25, 26 and 27 are curves of peak particle acceleration, displacement, and velocity, respectively, vs. slant range for receiving stations on both an alluvium and hard rock.

STRUCTURAL RESPONSE

The region of interest has been determined as that area within a range of about 130 km. This is the maximum range at which a threshold of perception acceleration of 0.001 g should be detectable on alluvium from a 50 kt explosion. Within this 130 km radius, larger centers of population are concentrated near Vernal, Utah; and Grand Junction, Rifle, Fruita, Meeker, Rangely, Glenwood Springs, Craig and Steamboat Springs, Colorado. In addition, the Dinosaur and Colorado National Monuments are in the vicinity and there are ranch buildings and highway structures within a few miles of the site, all of which should be investigated. Commercial structures in the area are primarily constructed of brick masonry and the residential structures generally of either wood frame and siding or wood frame and cement asbestos. The larger structures include a few buildings about six stories high in Grand Junction, while those in other towns have maximum height varying from two to four stories. Possibility of minor damage would be confined to an area of about 30 km radius, the distance within which accelerations in excess of 0.02 g would be experienced. There are no centralized population centers within this distance.

Ground Water

To assure protection of ground water resources, which is of prime concern to the AEC, detailed evaluations are planned for this project. Preliminary information indicates the following:

1. The event is not in a region of high ground water supply or usage.

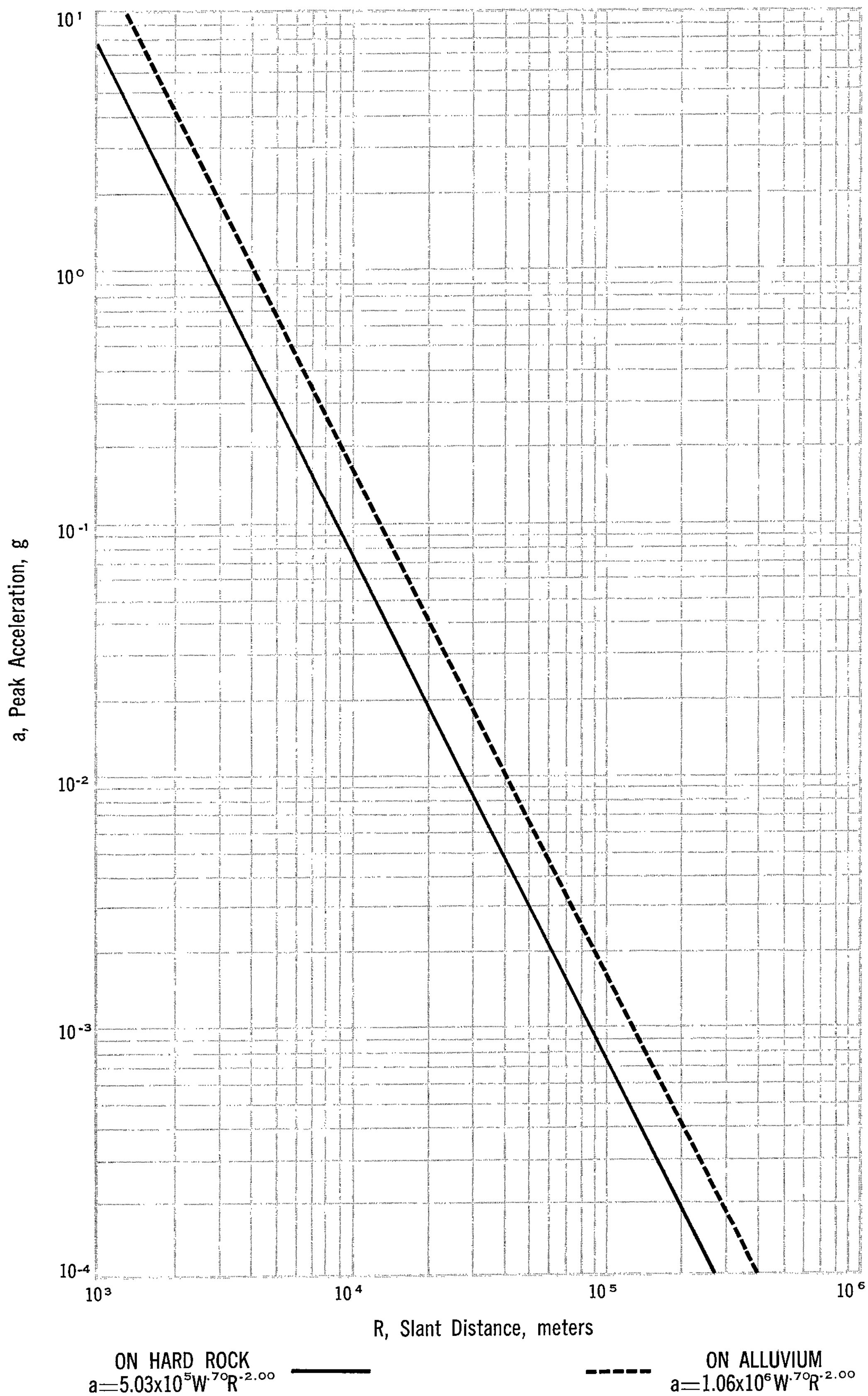


Figure 21. Predicted peak surface particle acceleration versus slant distance, Project Bronco.

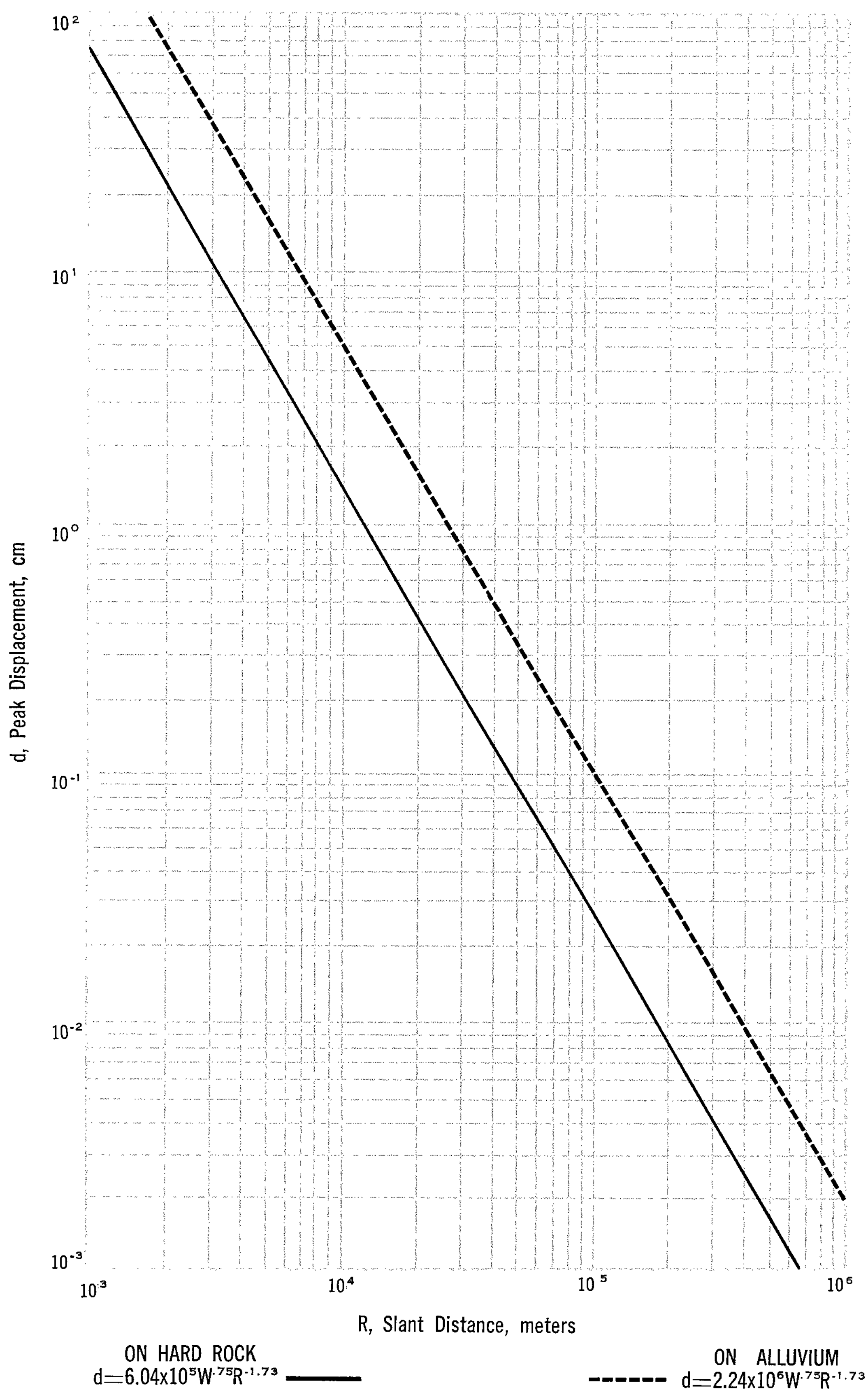


Figure 22. Predicted peak surface particle displacement versus slant distance, Project Bronco.

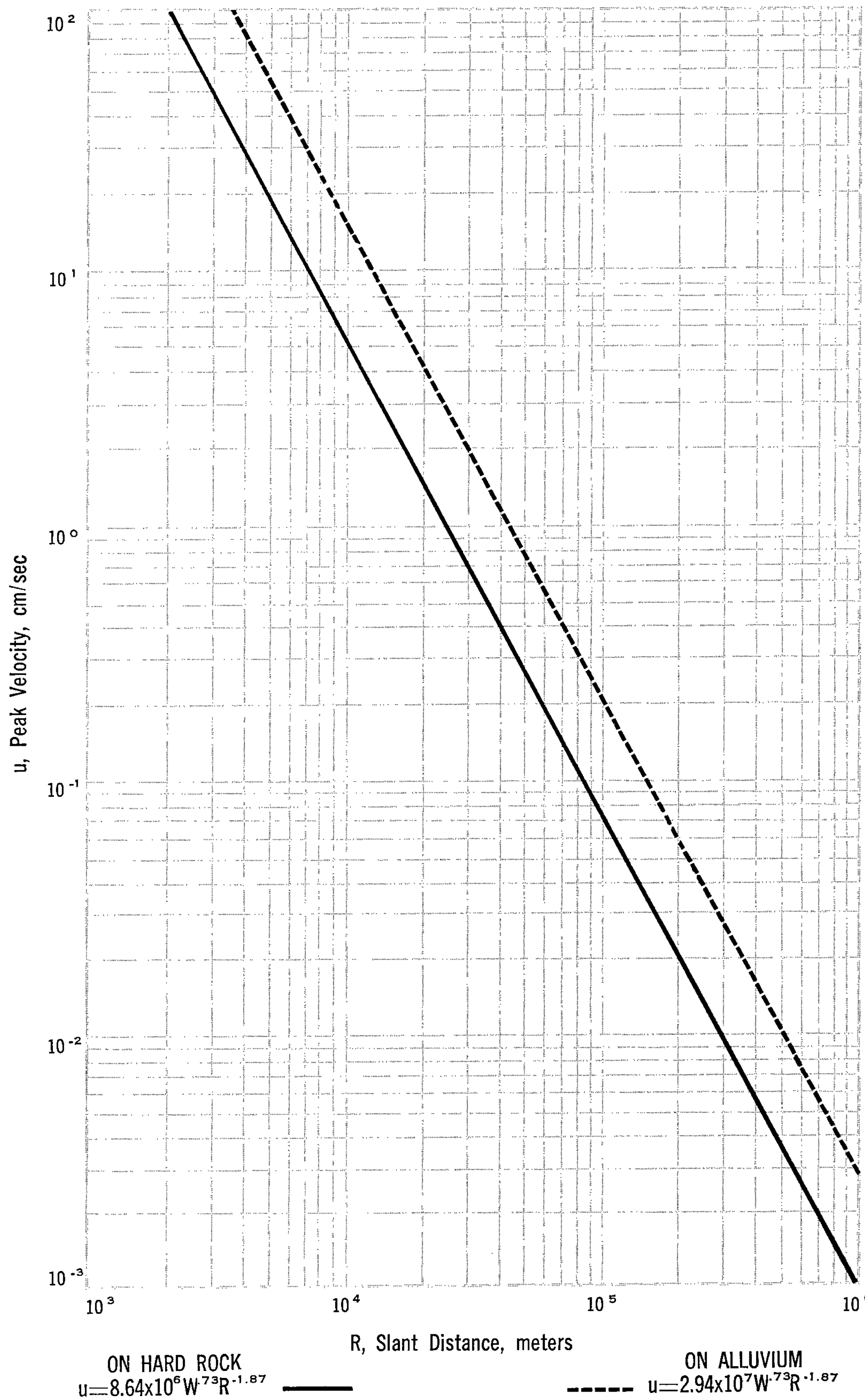


Figure 23. Predicted peak surface particle velocity versus slant distance, Project Bronco.

2. The chimney zone is only slightly water bearing although a possible water-productive zone exists in overlying formations.
3. Fracturing and chimney development by the nuclear explosion will not intersect water bearing shale in the overlying formations.

A detailed assessment of ground water problems requires information on the hydrology of the site area and region. The present study, however, indicates that barring unforeseen adverse conditions, which may be exposed by the hydrologic testing, there are no significant hazards to the ground water.

Bioenvironmental Safety

Preliminary evaluation indicates that the only potential bioenvironmental problem area is associated with the release of radioactivity to the biosphere. Such release is highly unlikely. Ground shock does not appear to be a hazard to the local ecology.

The area immediately surrounding the Project Bronco site, particularly the valley floor of Yellow Creek, consists of dry range land. The area is a major winter grazing area for the western mule deer. Possibly the largest single herd in existence (locally estimated to number as many as 100,000 animals) passes through the Bronco site area on its winter foraging. The herd summers in the White River National Forest directly east of the site area, and passes through the Meeker-Rangely area proceeding as far west as the Utah State Line in its migration. The White River Basin is becoming a very important big game hunting area. It is understood that because of the hunting pressures, the Colorado Game, Fish and Parks Department is considering the re-establishment of buffalo in the basin, since this area was historically one of the most heavily populated areas for buffalo on the western slope of the Rockies.

Field inspection indicates that the principal vegetation is Pinon Pine and Western Cedar (Juniperus species) on the uplands. Because of the rugged erosion of the area there are many swale areas which favor collection of moisture and consequently maintenance of good stands of native grasses, making the area suitable for open grazing. Under present land management and administration, local ranchers use the basin area by permit for summer grazing of domestic livestock.

Off-site Radiological Safety

The proposed scaled depth of burial for Project Bronco is about 910 feet/kt$^{1/3}$. This is more than a factor of two greater than that scaled depth normally considered necessary for containment of radioactive material. The probability of any stemming failure is extremely small; however, minor release of radioactive effluent cannot be ruled out. In such a case, the major radionuclides should be xenon, krypton, and iodine and their decay products. The distribution and dilution of any airborne effluent release at shot time can be controlled by detonating the nuclear explosive under selected meteorological conditions.

Based on the worst credible release assumptions, it is believed that meteorological conditions can be selected such that, with proper operational control and monitoring, there will be no excessive exposure to the public from such an inadvertent release of radioactive effluent.

The U. S. Public Health Service will conduct an environmental surveillance program to assure that any increase above background radiation levels can be promptly detected and acted upon as necessary.

Conclusions

No serious problem areas are foreseen in the selection of this site which could adversely affect the public health and safety. At a later date a comprehensive population, milk cow and dairy survey will be conducted to obtain more definitive data. Further data will be required on mines, structures, soils, resources, meterology, and hydrology to make a complete evaluation of the site. It is not anticipated that these data will impose serious restriction on the project.

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